A PALAEOMAGNETIC STUDY OF IGNEOUS ROCKS FROM EASTERN AUSTRALIA,

with special reference to rock bodies of Mesozoic age.

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STATEMENT

The studies described in this thesis were carried out by the writer while a full-time research student at the Australian National University during the period April 1959 to September 1962. The author held a Commonwealth scholarship during that period. Results from the first 14 months work were destroyed in a fire in the Cockcroft building of the School of Physical Sciences on July 6th, 1960, as a result of which an extension of time of 6 months was granted. The loss due to the fire was less than might otherwise have been expected because my annual report, which is a requirement of the tenure of my scholarship, was being typed in another building at the time and so was not destroyed; also duplicates were saved of work done jointly on the Gingenbullen Dolerite, Gibraltar Syenite, Prospect Dolerite and Cygnet Alkaline Complex. The losses due to the fire are given in Table 1.1. The work described in chapter 7 was carried out in conjunction with Mr. R. Boesen and Mr. E. Irving of this Department, and Mr. L. Hastie, of the University of Tasmania, contributed to the work described in chapter 9. Mr. K. Williams of the Geology Department of the Australian National University examined some of the polished sections described in chapter 4. Details of the work done in collaboration with other people are given in the appropriate part of the text. Apart from this the work is my own. The thesis has never been submitted to another university or similar institution.

William Archer Robertson

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Canberra, 1962

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SYMBOLS AND ABBREVIATIONS

a Semi-angle of the cone of confidence about the mean direction, within which the true mean direction lies with a probability P = 0.95.

a Chapter 2 only, $\frac{1}{2}$ side of square coil.

A Argon

B Number of Sampling Sites.

b Between site precision.

C‡ Contact stability test.

CRM Chemical Remanent Magnetization.

$\underline{D}$ Declination, clockwise east from True North (TN).

dm Semiaxis of oval of confidence perpendicular to dp.

dp Semiaxis of oval of confidence on great circle passing through point of observation and ancient pole position.

g Suffix used to represent a group of sites.

$\underline{H}_d$ Destructive field (equivalent to coercivity of remanence ~~(old H)~~ in oersteds).

$\underline{H}_p \sim$ Peak value of alternating magnetic field in oersteds.

$\underline{H}_{sat}$ Field in oersteds required to produce $\underline{M}_i$ sat.

$\underline{I}$ Inclination measured positively downwards from the horizontal plane.

IRM Isothermal Remanent Magnetization in e.m.u./cc.

k Fisher's best estimate of precision

K Potassium.

l North direction cosine.

$\underline{L}$ Vector of secondary magnetization.

MP Magnetic properties.

m East direction cosine.

$\underline{M}_n$ Untreated NRM results.

$\underline{M}_i$ sat. Saturation IRM in e.m.u./cc.

$\underline{M}$ Intensity of magnetization in e.m.u./cc. $\times 10^{-6}$ (or stated).

$\underline{M}_o$ Initial intensity of NRM.

m.y. Million years.

NRM Natural Remanent Magnetization.

n Downwards direction cosine.

$\underline{N}$ Number of specimens.

$\underline{O}$	Vector of primary direction of magnetization.
P	Probability.
$\underline{Q}$	Is the ratio of precision after partial demagnetization to that before.
$\underline{R}$	Resultant length of a group of unit vectors.
r	Suffix used to denote all results from a rock body.
S	Number of samples.
s	Suffix used to represent a site.
TRM	Thermo-remanent magnetization.
Th	Thermal, temperature measured in degrees centigrade.
w	Within site precision.
X	Palaeolatitude.
Z	The palaeomagnetic pole.

κ	kappa	The precision of a group of unit vectors calculated using Fisher's analysis of dispersion on a sphere.
ε	eta	The angle between the true mean direction and that of the specimen in Fisher's analysis of dispersion.
ϕ	phi	Latitude
λ	lambda	Longitude.
ψ	psi	ancient co-latitude.
χ	chi	Susceptibility in e.m.u./cc x 10^{-3} in a field of 0.5 oersteds.

CHAPTER 1 INTRODUCTION

1.1 Scope of the work.

Palaeomagnetism is the study of the direction of ancient or 'fossil' magnetization of rocks. If the measured direction in a rock sample is the direction acquired in the earth's magnetic field at the time of formation, defined as the primary (O) direction, and if the age and orientation of the rock is known, the result may be used to study the magnetic field at that time. To do this it is necessary to provide evidence for supposing that the direction obtained is primary, and therefore reflects the earth's magnetic field at the time of formation. A succession of such directions from rocks of increasing age may then be used to show changes in the magnetic field in previous epochs relative to the sampling area.

This thesis is mainly concerned with the observation of 'fossilized' magnetization directions in igneous rocks from eastern Australia formed during the Mesozoic Era, and from which the direction of the magnetic field at that time may be inferred: directions from some Tertiary rocks were also studied for comparison. During these studies it was found necessary to supplement the apparatus existing in the Department of Geophysics with an oven for thermal demagnetization. I constructed de-gaussing coils for this (chapter 2).

Samples from many rock bodies were obtained and their direction of magnetization studied. The age of the rocks studied is controlled by their stratigraphic relations, and in many cases by K-A isotope age determinations. The directions were subjected to field and laboratory tests of stability. The results have been analysed statistically and the mean from each rock unit obtained. These directions have been compared with each other to provide a picture of the variation of the earth's magnetic field in eastern Australia in the Mesozoic. Finally the Australian results have been compared with directions from other parts of the world.

<u>1.2 Acquisition of magnetization by rocks.</u> Of the ways in which rocks may acquire a natural remanent magnetization (NRM), 4 are important in the present study. (1) Rocks acquire a Thermo-remanent magnetization (TRM) when they cool through the Curie Points of the constituent magnetic minerals in a magnetic field. Thus igneous rocks become magnetized when they cool in the earth's magnetic field (Nagata 1953; Thellier 1938, 1951). (2) Chemical remanent magnetization (CRM) may be acquired by rocks that undergo chemical change in a magnetic field, (Haigh, 1958; Kobayashi, 1959). (3) Isothermal remanent magnetization (IRM), will be acquired by rocks at room temperature subjected to a magnetic field larger than the

lowest coercive force of the magnetic mineral in the rock, commonly more than 100 oersteds. (4) Viscous magnetization (Rimbert, 1956) may be acquired in much lower magnetic fields (such as that of the earth) if the rock remains in it for a sufficiently long time.

It is convenient to use Creer's (1957) nomenclature to differentiate between components acquired by rocks at different times: (1) A primary (O) component acquired at the time the rock is formed. (2) A secondary (L) component acquired later than O. L may be the vector sum of more than one component. (3) A temporary component acquired between collection and measurement. In general TRM of igneous rocks yields O components whereas IRM and viscous magnetization give L components. CRM may give either an O or an L component according to the time of chemical change; if it is due to weathering it renders the rock unsuitable for palaeomagnetic work as it masks the O component.

1.3 Relevent previous work. William Gilbert (1600) was the first to realize that the present earth's magnetic field approximates that of a uniformly magnetized sphere and subsequent to this details of the geomagnetic field were obtained at Observatories in various parts of the world. It was not until the late nineteenth century that Folgheraiter (1897, 1899), using an astatic magnetometer similar to one first used by Melloni (1853), showed that the magnetization in baked Etruscan pots was very stable, the first well-described measurement of TRM. A little later Brunhes (1905, 1906) was the first to measure the magnetization of clays baked by lavas and showed that they acquired a TRM by heating in the earth's magnetic field.

A detailed study of the magnetization of the lavas of Mount Etna by Chevallier (1925) showed, by comparison of directions from historic flows with directions measured at magnetic observatories, that the lavas became magnetized parallel to the magnetic field at the time of cooling, and he was able to use directions from older lavas to trace the secular variation in pre-historic times.

Mercanton (1926 (a) and (b), 1931, 1932), measuring magnetization directions in lavas from many countries, showed that reversals are a world-wide phenomenon; he made the first palaeomagnetic measurements on Australian rocks. Pertinent laboratory work by Königsberger (1932, 1938) and Thellier (1938, 1946, 1951) laid a good foundation for the development of palaeomagnetism.

Interest in the earth's magnetic field was stimulated by theories of its origin put forward by Elsasser (1946, 1947, 1956), Blackett (1952), Runcorn (1954, 1956(a)) and Herzenberg (1958). Its axial dipole nature over the last 20 million years was demonstrated by Hospers (1953, 1954, 1955). Hospers from field studies in Iceland and Roche (1950, 1951, 1953) in France published evidence supporting the postulate of reversals of the earth's field. Concurrent with this progress the design of higher sensitivity magnetometers such as the 'spinner' of Johnson (1938) and the elegant astatic magnetometer of Blackett (1952), which was adapted to measure rock discs (Collinson, Creer, Irving and Runcorn, 1957), greatly increased the range of rocks available for magnetic study.

In the decade following 1950 research in palaeomagnetism developed rapidly along two lines. (1) Active research, especially in Japan and France, into the complex magnetic properties of ferrimagnetic minerals in rocks, is summarized by Nagata (1953), Nicholls (1955) and Uyeda (1958), and a general theory to account for these properties was given by Neel (1955), and has been developed by Stacey (1958(a) and (b)) and Verhoogen (1959). (2) At the same time the possibility of testing the hypotheses of polar wandering and continental drift using palaeomagnetic results (Creer, Irving and Runcorn, 1954, 1957; Graham, 1955; Blackett, 1956; Irving, 1956(b), 1957, 1959; Runcorn 1956(a) and (b), 1959(a); Howell and Martinez, 1957; Creer, Irving, Nairn and Runcorn, 1958), led to the need for many accurately determined directions and pole positions for a sequence of rocks through geological periods from different continents. My training and experience has been in geology and field studies and the emphasis in this work is on the second of the above lines.

The work of Irving and Green (1958) showed that their palaeomagnetic results suggested a path of polar wandering relative to Australia but it was evident that both the direction and rate of movement of the pole relative to Australia were irregular, and many more detailed observations were required. There are great gaps in the record, for instance in the Mesozoic Era, and the work described in this thesis was designed to increase our knowledge of the field during this period. When I began this work only one set of detailed results, from the Tasmanian dolerite (Jaeger and Joplin, 1955; Almond, Clegg and Jaeger, 1956; Irving, 1956(a)) and preliminary results from the Brisbane Tuff, were available from the Mesozoic of Australia. My work described here goes some way towards filling the gap by reporting results in the Triassic, Jurassic and Cretaceous periods, some of which are established in fair detail.

1.4 Plan of the Work. Just as many formations are unsuitable for palaeontological study due to lack of fossils or poor preservation, so also many rock bodies are not suited to palaeomagnetic study because of weak or unstable magnetization. Hence the preliminary field survey ranged over a wide area and comprised rocks of many ages in an attempt to find material suitable for palaeomagnetic study. The rock units sampled are shown in Table 1.1 in the order in which they were collected together with a synopsis of the work done on them. This preliminary work on 20 rock units is described in chapter 3. As shown in the table considerable loss of data was caused by the fire in the Cockroft Building of the School of Physical Sciences at this University on July 6th, 1960, in which all data up to that time was destroyed. After the fire all primary data was duplicated, the duplicates being kept in a separate building: unpromising rock units were not considered further, but specimens from bodies that appeared to be suitable for palaeomagnetic study were remeasured.

Of the 20 rock units reconnoitred 9 were judged to be suitable for further study. The direction and intensity of NRM of many specimens from each of these units was measured. Selected specimens were tested for stability and all specimens were magnetically or thermally cleaned. The primary data for this work is given in appendices at the end of the thesis, numbered according to the chapter in which they were described. The data were analysed statistically and mean directions for each rock unit were calculated. These data are given in tables opposite or

TABLE 1.1

ROCK BODIES SURVEYED

No.	Description	Latitude S	Longitude E	Age
1	Granites from Mt. Isa Area	25	139	P€
2	Murrumbidgee Bathylith	36	149	S
3	Tumut tunnel and Cabramurra Basalts	35	148	T ?
4	Gibraltar Syenite	34.5	150.4	J1
5	Gingenbullen Dolerite	34.6	150.3	J ?
6	Prospect Dolerite	33.8	150.9	J1
7	Kelly's Point Complex	36	150	T and D
8	Moruya Bathylith	36	150	D

Work Done								Remarks
S	NRM	P.D.	TRM	Ct	MP	AFD	ThD	
50	✓							Collected during granite sampling for age determination by B.M.R. Results lost in fire. Some too weakly magnetized, others probably struck by lightning.
11	✓							Results lost in fire. Some too weakly magnetized, others weak and scattered directions.
4	✓							Samples collected by Dr's Lovering & McDougall. Lost in fire. No agreement between specimens.
10	✓				✓	✓		K-A age from hornblende Samples collected by R. Boesen.
8	✓	A.F.			✓	✓		K-A age from plagioclase× Directions reversed. Samples collected by R. Boesen.
10	✓				✓	✓		K-A age from biotite in contact zone. Samples collected by R. Boesen.
20	✓							Initial measurements lost in fire. Remeasurement showed most sites scattered. No time for partial demagnetization.
5	✓							Results lost in fire. Directions scattered. Fresh outcrops inadequate.

× Subject to calibration correction

TABLE 1.1 continued

No.	Description	Latitude S	Longitude E	Age
9	Murrumburrah Basics	34	149	T ?
10	Painter Porphyry	35.3	149.1	D
11	Cygnet Alkaline Complex	43.2	147.1	Ku
12	Mount Dromedary Complex	36.3	150.1	Ku
13	Milton Monzonite	35.3	150.4	P-J
14	Coles Bay Granite	42	149	D
15	Ruby Hill Basanite	30.2	150.2	T ?
16	S.E. Queensland Tertiary Igneous Rocks	127	153	T
17	Noosa Heads Complex	26.4	153.1	Ju

Work Done								Remarks
S	NRM	P.D.	TRM	Ct	MP	AFD	ThD	
4	✓							Small plug with eclogite inclusions. Directions random at P=0.0
3	✓	A.F.				✓		Samples collected from excavation for Mount Stromlo spectograph. Attitude of rock doubtful.
68	✓	A.F.	✓	✓	✓	✓		K-A age from 3 minerals Stability tested.
78	✓	A.F. & Th.	✓	✓	✓	✓	✓	K-A age from 3 sites and 3 minerals. Detailed study of stability for many rock types.
12	✓	A.F.	✓			✓		K-A age *160 m.y. minimum* Good example of removal of secondary component by P.D. in A.F.
2	✓					✓		Appears to be stable. Need more samples from more sites.
3	✓	A.F.						From basanite dyke cutting a breccia pipe containing eclogite. Samples collected by G. Halford.
54	✓	A.F.	✓		✓	✓		Ages not accurately known. Intrusives and lavas used.
22	✓	A.F.				✓		K-A age from sill and boss using hornblende and biotite. Gives a well-dated reversal.

TABLE 1.1 continued

No.	Description	Latitude S	Longitude E	Age
18	Brisbane Tuff	27.5	153.0	Rm
19	Enogera Granite	27.5	153.0	P ?
20	Felsite Dyke from Queensland University Mine.	27.5	153.0	?

S = Number of samples, NRM = Natural remanent magnetization, P.D. = Partial demagnetization, A.F. = Alternating magnetic field, Th = Thermal, TRM = Applied thermo-remanent magnetization, Ct = Contact stability test, MP = Magnetic properties, AFD = Demagnetization in an alternating magnetic field. Th.D = Demagnetization by heating.

Work Done								Remarks
S	NRM	P.D.	TRM	Ct	MP	AFD	ThD	
12	✓	A.F.				✓		Middle Triassic fossil flora. Small stratigraphic range, may contain secular variation component.
3	✓							Random distribution at P=0.05.
3	✓							May get a lead age later. Specimens too weakly magnetized.

adjacent to the appropriate text. The results for the 9 rock units studied in this way form the subject matter of chapters 4 to 10. A more detailed study of stability and comparison of cleaning techniques is described for the Mount Dromedary rocks in chapter 4.

When I came to this University astatic magnetometers and alternating field demagnetization apparatus were available in the non-magnetic hut. As a first step we constructed a non-magnetic oven to facilitate thermal studies. My part in this was to make and test a set of degaussing coils, which is described in chapter 2.

Pole positions were calculated from the mean directions obtained in chapters 4 to 10, so that results from different places could be directly compared. In Chapter 11 the palaeo-climatic and palaeotemperature evidence from Australia is compared with the palaeolatitudes derived from these poles in the Triassic, Jurassic and Cretaceous periods, with a view to examining the hypothesis of polar wandering. Finally in chapter 12 my results from the Mesozoic of Australia together with that already published are compared with results of similar age obtained by other workers from other continents to test the hypothesis of continental drift.

1.5 Sample Collecting. A rock body is only suitable for palaeomagnetic sampling if:- (1) It is adequately exposed, (2) Sufficient of the rock is unweathered, (3) Specimens from it are strongly enough magnetized to deflect the magnetometer, (4) The structural environment is comparatively simple so that it is possible to ascertain any subsequent movement that has occurred.

In eastern Australia any slight red staining in igneous rocks in the field is indicative of weathering which will cause masking of the primary (O) component, and suitable material is in general only available in quarries, road and rail cuttings, sea-cliffs, or blast holes, severely limiting the number of sites available in any rock body.

In this work 2 or more oriented samples were collected from each site to check orientation errors. Samples were oriented by standard geological techniques and orientation was accurate to within 2^{o}. Sufficient samples were taken to justify a statistical analysis as described in section 1.6. As far as possible sites were chosen so that secular variation would be averaged out in the mean; this may be done for intrusive bodies if outcrops allow adequate sampling since the time taken for the Curie Point isotherm to recede from the margin to the centre of the body is greater than that of a secular variation cycle (Jaeger and Green, 1956, Jaeger, 1958, 1961).

1.6 Measurement and analysis. From the rock samples collected in the field 2 or more cylindrical specimens, 3.5cms in diameter and either 7 or 35mm thick, were cut normal to the oriented surface with non-magnetic tools, care being taken to preserve the orientation marks. The direction and intensity of magnetization of these specimens was measured on either a short period (Irving, 1956(a)) or long period (described by Green, 1959) astatic magnetometer essentially similar to those previously constructed (Blackett, 1952; Collinson, Creer, Irving and Runcorn, 1957).

Magnetization directions obtained from specimens are specified by the declination ($\underline{D}$) measured clockwise from true north and the inclination ($\underline{I}$) measured positively downwards from the horizontal plane. The direction cosines (l, m, n) of one specimen are then:-

$$l_1 = \cos \underline{D} \cos \underline{I}, \quad m_1 = \sin \underline{D} \cos \underline{I}, \text{ and } n_1 = \sin \underline{I} \qquad \ldots (1)$$

Fisher (1953) has shown that the best estimate of the mean of a set of N specimen directions from a site is given by:-

$$l_s = \sum_{n=1}^{N} \frac{l_1}{\underline{R}}, \qquad m_s = \sum_{n=1}^{N} \frac{m_1}{\underline{R}}, \qquad n_1 = \sum_{n=1}^{N} \frac{n_1}{\underline{R}} \qquad \ldots (2)$$

$$\text{where } \underline{R} = \left\{ \left(\sum_{n=1}^{N} l_1\right)^2 + \left(\sum_{n=1}^{N} m_1\right)^2 + \left(\sum_{n=1}^{N} n_1\right)^2 \right\}^{\frac{1}{2}} \qquad \ldots (3)$$

He suggested that the measured directions of specimens may be regarded as distributed over a sphere with a probability density

$$\frac{\kappa}{4\pi \sinh \kappa} \exp\ (\kappa \cos \varepsilon) \qquad \ldots (4)$$

where ε is the angle between the true mean direction and that of the specimen. κ is a measure of precision, and Fisher showed that the best estimate of it, k, is given by:-

$$k = \frac{N-1}{N-R} \qquad \ldots (5)$$

He also showed that the accuracy of the estimate of the true mean direction may be specified by the semi-vertical angle, a, of the cone about the mean direction, given by:-

$$\cos a = 1 - \frac{N-R}{R}\left\{P^{-1/N-1} - 1\right\} \qquad \ldots (6)$$

Here a probability, P = 0.05 is used.

Fisher's analysis may be used to combine results from any level, such as specimens or sites, to give a mean at a higher level, such as sites or rock units. To avoid confusion and facilitate comparison the following system of suffices has been adopted here to designate the levels to which D, I, R, N, k, and a refer:- The left-hand suffix refers to the level from which the data are taken, and the right-hand suffix refers to the level at which the data are combined: Where intermediate levels are used, such as combination of specimen directions into site directions and then from sites to rock bodies, the intermediate suffices refer, from the left, to the levels through which the final statistic is obtained. 1 represents a specimen, which is measured by the magnetometer, 2 represents a sample, collected in the field, s represents a site, which is a single collecting area such as a blast hole, road cutting, or quarry, g represents a group of sites with some common denominator such as rock type, and r represents the whole rock body. Thus $\underline{D}_{1sr}$ is the declination in a rock body obtained from site means which come from the mean of specimen directions.

Another way of representing results is the calculation of pole positions (Creer, Irving and Runcorn, 1957). This allows comparison to be made between results from different places. The pole position may be calculated from a given declination ($\underline{D}$) and inclination ($\underline{I}$) obtained at a place with geographical co-ordinates (ϕ^1, λ^1), using the property of a dipole field that the magnetic co-latitude (ψ) bears the simple relation to the inclination (I) -

$$\cot\psi = \tfrac{1}{2}\tan \underline{I} \qquad \ldots (7)$$

If the present geographical co-ordinates of this pole are (ϕ, λ) they may be obtained by solving the spherical triangle on the earth's surface using the formulae:-

$$\sin\phi = \sin\phi^1 \cos\psi + \cos\phi^1 \sin\psi \cos \underline{D} \qquad \ldots (8)$$

and

$$\sin(\lambda - \lambda^1) = \frac{\sin\psi \sin \underline{D}}{\cos\phi} \qquad \ldots (9)$$

In some rock units the within site scatter was small and it was thought worth while to do a within and between site analysis as developed by Watson and Irving (1957); in these cases the within (w) and between (b) site precisions are given.

1.7 Field studies of stability. Certain field tests may be used to indicate whether the measured directions are likely to have been retained since the rock was formed. Positive results for these tests support the idea that the magnetization direction in the rock reflects that of the field at the time of formation. These tests are:-

(1) Consistency test. If directions from a group of samples from a single unit show a small scatter then all factors causing dispersion, notably randomly or systematically directed components are likely to be small. There is still the possibility of secondary components all of such a size as to rotate all the directions in a group: however many results from single sites show variable stability, and this variability is likely to be more pronounced when taken over the whole rock unit.

(2) Deviation test. If directions from a rock unit are away from the present field direction they must be stable in the present earth's field. Reversals add much weight to this test. 'Stringing' of directions along a great circle towards the present or dipole field directions indicates partial instability.

(3) Contact test. Directions from sediment baked by an intrusion similar to those of the igneous rock but different from those of the unbaked sediment are good evidence that the magnetization was acquired at the time of intrusion and is probably due to TRM. The possibility that both baked sediment and intrusion acquired their direction from some later source, while it cannot be precluded, is very unlikely in view of the difference in direction from the unbaked sediment.

(4) Structure tests. Positive results for the fold and conglomerate tests of Graham (1949) indicate stability, since they show that no secondary (L) component has been acquired since the folding or deposition of the conglomerate, but opportunities for applying such tests are rare for igneous rocks, and no such suitable structure has been found in this work.

Commonly only field tests (1) and (2) are available for judging stability, so that additional laboratory tests are highly desirable. These have been developed to analyse the components present and are described in the next section.

1.8 Laboratory studies of stability. Igneous bodies have been shown to acquire a primary (O) TRM, when they cooled, in the direction of the earth's magnetic field (Chevallier, 1925; Hospers, 1953; Nagata, 1953; and others). Commonly, however,

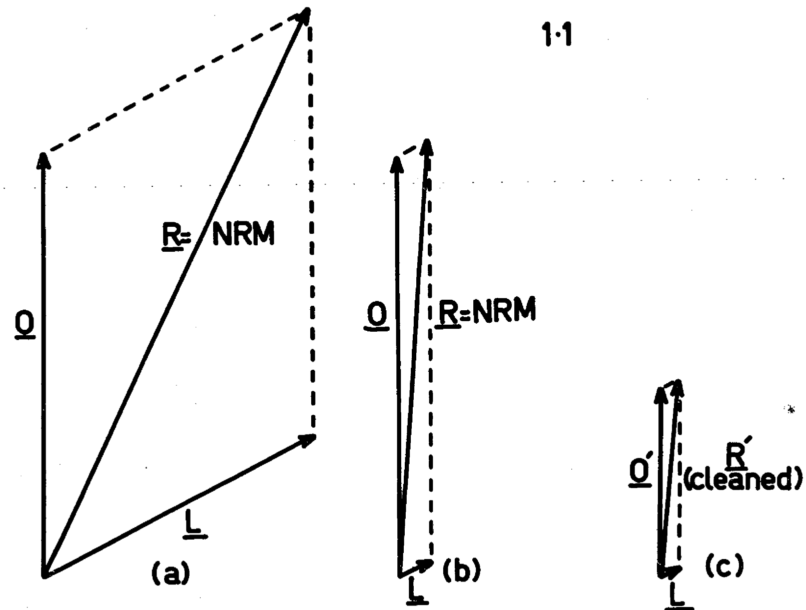


Fig. 1.1. Showing primary (O) and secondary (L) component vectors of NRM of rocks. (a) NRM of a 'partially stable' rock in which both O and L are large. (b) NRM of a 'stable' rock in which O is large and L is small. (c) Remanent magnetization after 'cleaning' a partially stable rock such as that giving result (a), in which the L component is reduced much more rapidly than the O component, yielding a direction similar to that given by the 'stable' rock.

a later secondary (L) magnetization is superposed (As and Zijderveld, 1958; Creer, 1957; Irving, Stott and Ward, 1961). The NRM of such a rock is the vector sum of O and L, and the rocks may be defined as 'partially stable', since the direction is only partly due to the O component. It follows that rocks in which only an O component is significant are defined as 'stable', and those in which the O component is absent or entirely masked as 'unstable'. The object of magnetic and thermal cleaning, which have been used extensively in this work, is to increase the $^{O}/_{L}$ ratio in partially stable rocks (Figure 1.1), and if possible to render L negligible.

The laboratory techniques that may give pointers to stability are:-

(1) Demagnetization of NRM by alternating magnetic fields.

(2) Thermal demagnetization of NRM.

(3) Thermal demagnetization of applied TRM.

(4) Magnetic properties in high fields ($M_{i\ sat.}$, H_d, H_{sat})

(5) Examination of thin sections.

(6) Examination of polished sections.

(7) X-ray powder photography.

(8) Various sophisticated techniques such as anhysteritic demagnetization, (Rimbert, 1957) partial thermal demagnetization, and anisotropy measurements, which will not be discussed here.

The apparatus used both for alternating magnetic field demagnetization (Irving, Stott and Ward, 1961), and for thermal demagnetization (Irving, Robertson, Stott, Tarling and Ward, 1961), has been previously described. The two methods are analogous, the difference is that the intensity after treatment depends in the case of alternating field demagnetization on the coercivity of the magnetic mineral grains in the specimen, and in the case of heating on the Curie Point spectrum. Specimens are treated in successively higher fields or temperatures, and the direction and intensity of magnetization is measured after each step. The ratio of intensity at each step to the initial intensity may be plotted against field or temperature, and these curves for different rocks may be compared. Comparison with curves from rocks of known stability characteristics gives a qualitative criterian of stability.

The above two types of apparatus may also be used for magnetic and thermal cleaning respectively (for example As and Zijderveld, 1958) in which all specimens from a group are subjected to a previously determined field or temperature treatment. The field or temperature required is that for which the ratio $\underline{O}/\underline{L}$ is a maximum. Two criteria that may be used to determine this are the rotation of the vector in the case of distributions strung towards the present field, or the more general reduction of scatter.

L is commonly composed of two components, a directed component (the secondary component of Creer (1957)) along the direction of the present or dipole field, and a randomly directed component (Creer's temporary component) commonly acquired during storage at random in the earth's field. Both components may form a different proportion of the total intensity in different specimens, presumably due to different coercivities or Curie Points of this component, causing stringing from and scatter about the O direction respectively. Both cause scatter and hence are minimized when the scatter is least.

Fisher's (1953) estimate of precision, k, the inverse of scatter, of a group of specimens from a site is used here as an objective criterian for minimizing L. Thus a group of specimens are treated in successively higher fields and temperatures until that giving least scatter may be determined; the remaining specimens are then cleaned in this field (or temperature). Comparison of the two methods using Mount Dromedary rocks (chapter 4) indicated that magnetic cleaning was the more effective for igneous rocks, and it has been used for the other rock units studied.

Specimens may be given a TRM by heating above the Curie Points of the magnetic minerals and cooling in the laboratory in the earth's magnetic field. Rocks for which TRM and NRM thermal demagnetization curves follow similar paths are believed to have retained their original TRM acquired on initial cooling until it was destroyed in the laboratory, and hence to be stable. Partially stable specimens may have parallel TRM and NRM curves in the higher temperature ranges.

Magnetic properties in high fields, and also susceptibility (χ), give useful information about the rocks, but these properties are not directly related to the stability of NRM acquired in a low field. Thin section examination is useful for naming and grouping rocks and testing for incipient weathering, but yields little information about the magnetic minerals.

Polished sections, supplemented where possible by X-ray powder photography, enable most of the ferrimagnetic minerals to be identified. Intergrowths and the shape and size of the ferrimagnetic minerals may also be seen. The relationship between stability and these factors, however, is still largely unknown but it is important to establish empirical relationships and a preliminary attempt has been made to do this for Mount Dromedary.

1.9 Age basis for the palaeomagnetic results. Most previous magnetic direction determinations have been obtained from lava flows and red beds which in general do not contain minerals suitable for radio-active isotope age determinations, and very commonly their geological age is only known by stratigraphic correlation within wide limits.

The rocks examined here have been selected to include as many as possible from which both magnetization directions and radio-active ages could be determined, in order to provide an adequate time basis for the palaeomagnetic results. In many cases stratigraphic control is also available.

The age of mineral separates from Mount Dromedary, Cygnet, Noosa Heads, Milton Monzonite, Gibraltar, Prospect and Gingenbullen has been determined in this department by the K-A isotope method (Appendix 11.1), and wherever possible 2 or more minerals from 2 or more sites have been used. This radio-isotope work was done by Evernden and Richards and the earlier results have been published (Evernden and Richards, 1962). The advantage of this is that the K-A age determinations give an upper age limit, due to the possibility of argon loss through diffusion, whereas the stratigraphic age of the rocks intruded give a lower limit to the age. Thus the palaeomagnetic results are contained in a good age framework.

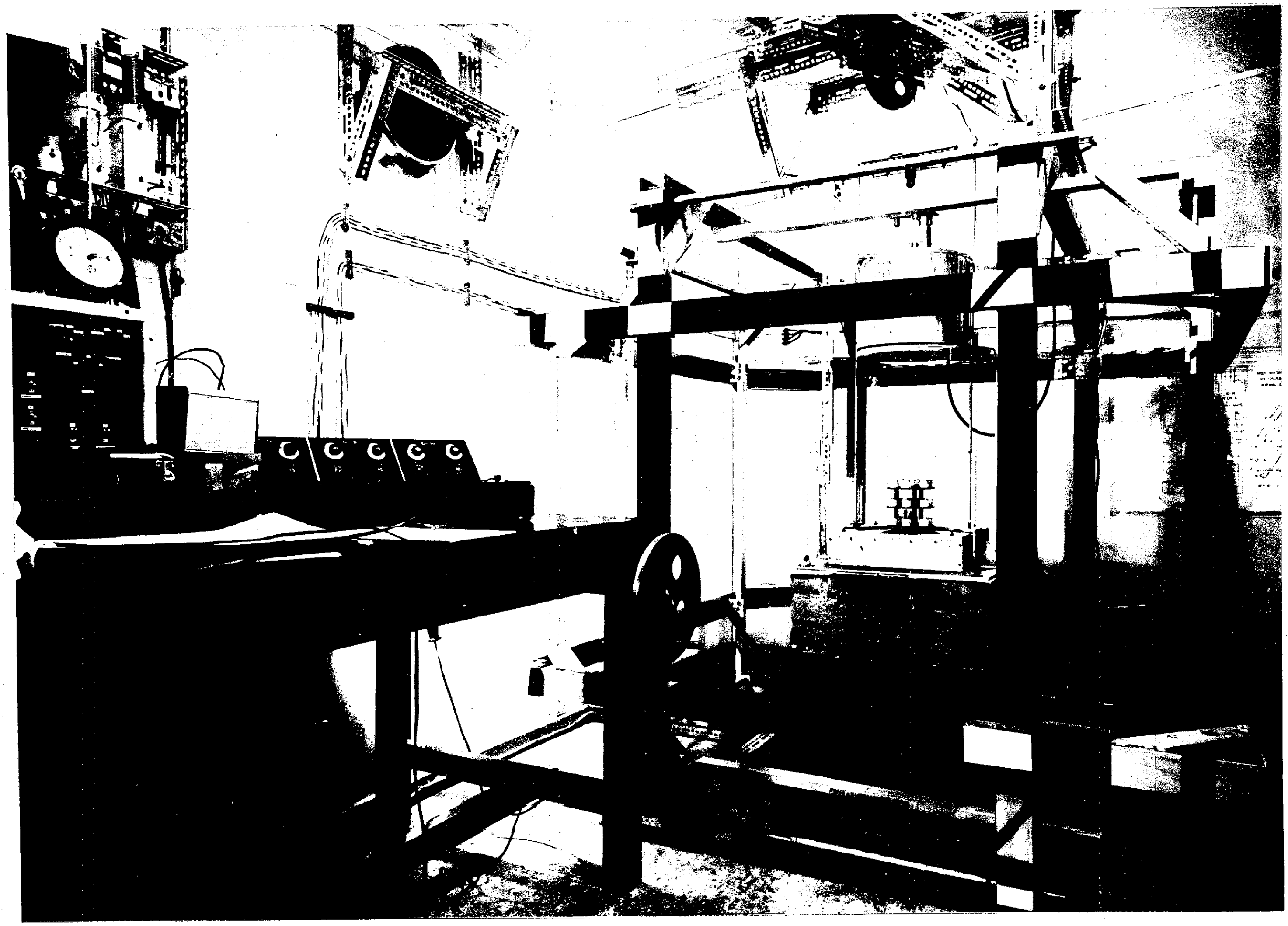


Fig. 2.1 The thermal demagnetization apparatus, showing specimens in the oven with the insulating jacket raised, the nulling coils and the controls.

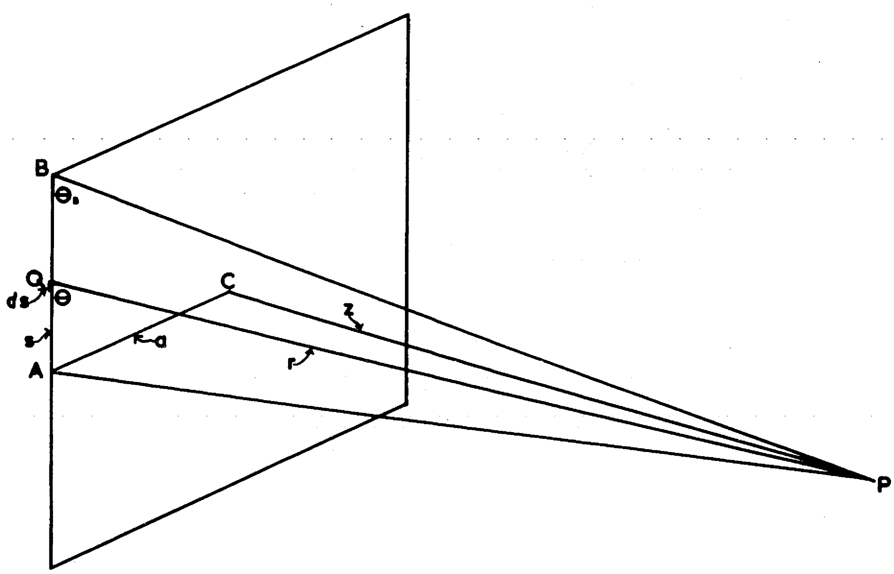


Fig. 2.2 <u>Diagram of the elements to calculate to the field on the axis of a square coil due to an electrical current flowing round it</u>.

CHAPTER 2. CONSTRUCTION AND TESTING OF A SET OF SQUARE DEGAUSSING COILS

2.1 The Purpose of the Coils. The coils were made to annul the earth's magnetic field in a cylindrical oven 18cm in diameter (Irving, Robertson, Stott, Tarling and Ward, 1961). It holds 40 specimens of 35mm diameter and 7mm thick (Figure 2.1). The object was to heat and cool sets of specimens to known temperatures in either zero or a known magnetic field so that the stability of specimens could be thermally cleaned.

Three pairs of orthogonal square coils were used. These are simpler to make, easier to instal, and provide better access than circular coils, and give comparable accuracy in nulling the field. It would be difficult to orient a single pair set in the Helmholtz position with their axis parallel to the earth's magnetic field.

2.2 Theoretical Considerations.

Let $AB = AC = a = \frac{1}{2}$ length of side of one square coil and

P be a point on the axis such that $CP = z$, and

Q a point on AB such that $AQ = S$

Also let $AQP = \theta$, and $QP = r$

Then $AP = (a^2+z^2)^{\frac{1}{2}}$

The field at P due to a small length ds of the coil at Q (Figure 2.2) carrying a current i is:-

$$dH = \frac{i\,ds\,\sin\theta}{r^2} \quad \text{.... Biot Savat's Law} \qquad \text{... 1}$$

but $ds = -(a^2+z^2)^{\frac{1}{2}} \operatorname{cosec}^2\theta \, d\theta$ and $\frac{1}{r^2} = \frac{\sin^2\theta}{a^2+z^2}$

$$\therefore \quad dH = -\frac{i \sin\theta \, d\theta}{(a^2+z^2)^{\frac{1}{2}}}$$

Integrating from A to B

$$H_{ab} = -\int_{\frac{\pi}{2}}^{\theta_b} \frac{i \sin\theta \, d\theta}{(a^2+z^2)^{\frac{1}{2}}} = \frac{i \cos\theta_b}{(a^2+z^2)^{\frac{1}{2}}}$$

but $\cos\theta_b = \dfrac{a}{(2a^2+z^2)^{\frac{1}{2}}}$

$\therefore$ Total field at P due to AB, $H_{ab} = \dfrac{i\,a}{(a^2+z^2)^{\frac{1}{2}}(2a^2+z^2)^{\frac{1}{2}}}$ ... 2

The axial component is $H_{ab} \cos CAP = H_{ab} \dfrac{a}{(a^2+z^2)^{\frac{1}{2}}}$

$$= \frac{i\,a^2}{(a^2+z^2)(2a^2+z^2)^{\frac{1}{2}}}$$

By symmetry over the whole coil the radial components cancel, so that the field due to the coil at P is $\dfrac{8\,i\,a^2}{(a^2+z^2)(2a^2+z^2)^{\frac{1}{2}}}$ ... 3

or $\dfrac{8\,i}{a} \left((1+x^2)^{-1}(2+x^2)^{-\frac{1}{2}} \right)$ where $x = \dfrac{z}{a}$

For the Helmholtz position the axial gradient must be zero, i.e. $\dfrac{\partial^2 H}{\partial x^2} = 0$

Now $\dfrac{\partial H}{\partial x} = -\dfrac{8i}{a}\left(\dfrac{3x^3 + 5x}{(x^2+2)^{3/2}(x+1)^2} \right)$ ... 4

and $$\frac{\partial^2 H}{\partial x^2} = -8i\left(\frac{(9x^2+5)(x^2+2)(x^2+1)-3x(3x^3+5)(x^2+1)-4x(3x^3+5x)(x^2+2)}{(x+1)^3 \quad (x+2)^{5/2}}\right) \quad \ldots 5$$

Hence for the Helmholtz position $6x^6 + 18x^4 + 11x^2 - 5 = 0$ ... 6.

The required solution is $x = \frac{z}{a} = 0.5445$, that is the axial component of magnetic gradient is zero at a distance of 0.5445 times the half length of the square from the centre of the coil.

Thus the required coil separation is 1.0890.a ... 7

If a current of i e.m.u. flows through a pair of square coils of ½ side length a, each containing n turns, then the field, H, at the centre, is from 3 ....

$$H = \frac{16\, i\, a^2 n}{(a^2+z^2)(2a^2+z^2)^{\frac{1}{2}}} \qquad \text{where } z = -.5445.a$$

$$\therefore H = \frac{8.143\, i\, n}{a} \qquad \text{e.m.u.} \ldots\ldots\ldots$$

If the field is measured in oersteds and the current in amps, then $H = \frac{0.8143\, i\, n}{a}$ ... 8

2.3 <u>Practical Considerations</u>. The size of the coils was limited by hut height and access to a side length of about 2 metres. Formats of welded aluminium were lined with empire cloth and leads were taken through plastic grommets to ensure insulation. Single enamel 18 s.w.g. copper wire in alternate layer windings, coated

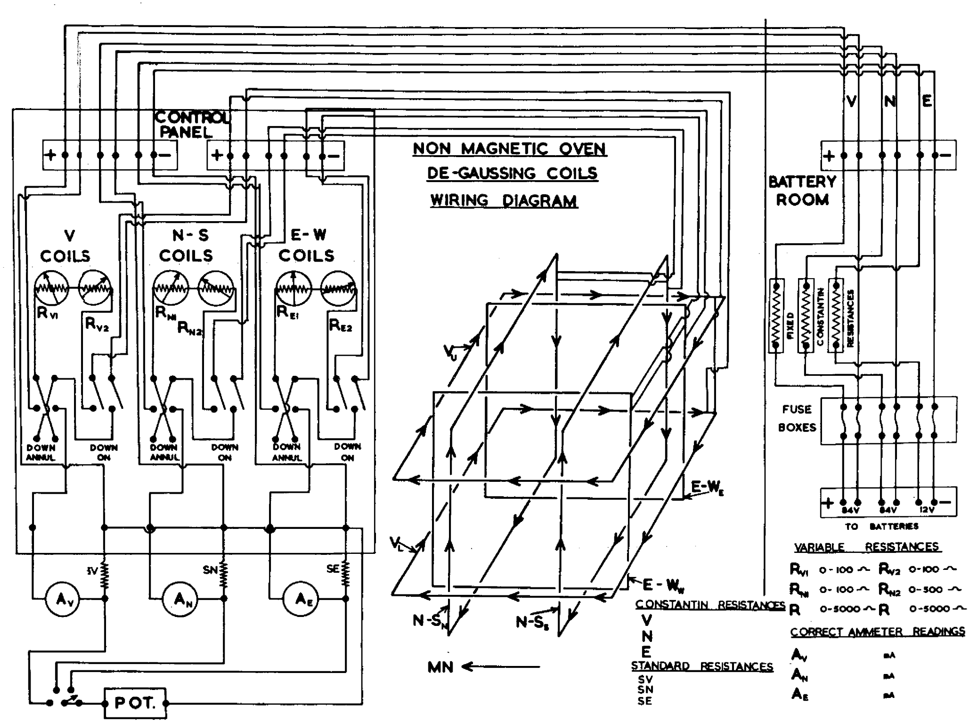


Fig. 2.3 <u>Electrical circuit diagrams</u> for the 3 orthogonal pairs of square coils.

with shellac, was used. Primary and secondary coils for the 6 squares were wound by rotation in a vertical plane in a specially made gantry, fitted with a counter. Table 2.1 gives details of the windings.

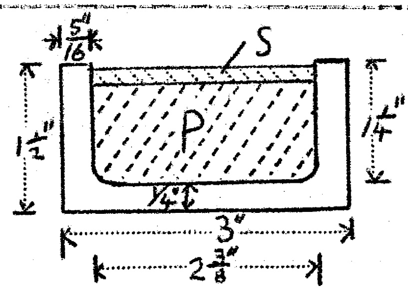
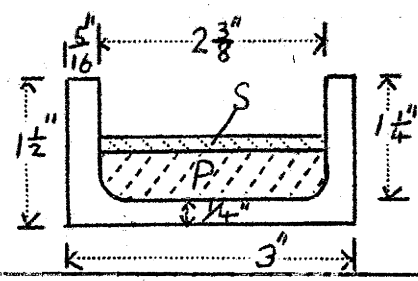
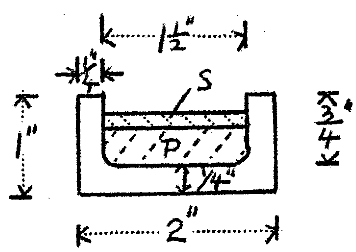
The N coil pair, with horizontal axes in the magnetic meridian to annul the horizontal component of the earth's magnetic field, rest on the floor of the hut. The E pair, with horizontal axes at right angles to the magnetic meridian, to annul any residual component, fit inside the N coils. The V pair, with vertical axes to annul the vertical component of the earth's magnetic field, fit outside the other coils, which support them.

Each pair of coils, which are connected in series, has a similar electrical circuit (Figure 2.3). The current is supplied by a bank of lead/acid batteries that will supply 84 volts. The current in each pair is adjusted by variable resistances (Rvi etc.) and measured by substandard Weston moving coil ammeters (Av etc.). A reversing switch is included in each circuit. Fluctuations of current due to temperature changes are kept to a minimum by a large constantin fixed resistance in series with each coil pair. A potentiometer circuit, which could be switched into any pair, and was also used to measure the temperature in the oven, was used for fine adjustment and current checking.

Table 2.2 gives the residual field in gamma at the centre of the oven due to various percentage errors in the currents in the

TABLE 2.1

SPECIFICATIONS OF SQUARE HELMHOLTZ COILS

COILS	ALUMINIUM FORMATS			
	Cross-Section of Channel in ins. Half Natural Scale	Outside length of square in ins.	Inside length of square in ins.	Separation of inner sides of coils in cms.
Bottom V. Top		72.22	177.06	90.26
N. N-S S.		69.00	168.87	85.01
E. E.W. W.		65.80	163.24	84.06

a = Effective ½ length of square, that is the mean half length for the appropriate winding.

	PRIMARY WINDINGS					SECONDARY WINDINGS			
a in cms	No. of Turns	Res. in Ohms.		Current in amps.		a in cms.	No. of turns	Res. in Ohms	
		Calc.	Meas.	Calc.	Meas.			Calc.	Meas.
89.74			66.7						9.6
	640	68.9		.093	.0926	91.39	82	8.9	
90.06			67.0						9.6
85.16			30.8						8.3
	310	31.2		.083	.0820	85.95	82	8.3	
85.16			30.8						8.3
81.88			7.2						5.3
	73	6.8		[x] .034	.0005	82.35	54	5.3	
81.83			7.1						5.3

x = allowing for 1° error in levelling V. coils and 2° error in orienting N-S coils.

TABLE 2.2

% Change in Current	ΔH, Change in field from current change in N-S coils in γ	ΔV, Change in field from current change in V coils in γ	Resultant field in oven in γ
0.10	24	54	59
0.20	48	107	118
0.25	61	134	147
0.30	72	161	176
0.40	96	214	234
0.50	122	268	294
0.60	144	321	352
0.75	183	402	442
1.00	243	536	558
1.50	365	804	883

V and N coils. It was possible to read the Weston meters to an accuracy of between 0.1 and 0.2 percent and thus to control the field due to the coils within 100 gamma. Field fluctuations of this order were produced by variations in the earth's magnetic field due to diurnal variations, magnetic storms and local disturbances so that the Weston substandard meters were adequate to measure the current in the coils. Current values about 3 times more accurate may be obtained using the potentiometer, which would only increase the accuracy if the disturbances could be better controlled.

2.4 Preliminary Testing. The currents required to annul the earth's field, called the compensating currents, were found experimentally for each pair by altering the current in one pair by steps while the current in the other pairs was kept constant, and observing the effect on a dip circle for the V coils and on an oscillating magnet for the N and E coils set at the centre of the system.

To balance the V coils the dip circle was set in the magnetic meridian. The current through the V coils was adjusted until the needle was approximately horizontal. Deviations from the horizontal were measured for small variations of current. Each direction was obtained as a mean of eight dip needle readings, (both ends, repeated with the circle reversed, and all repeated with the needle

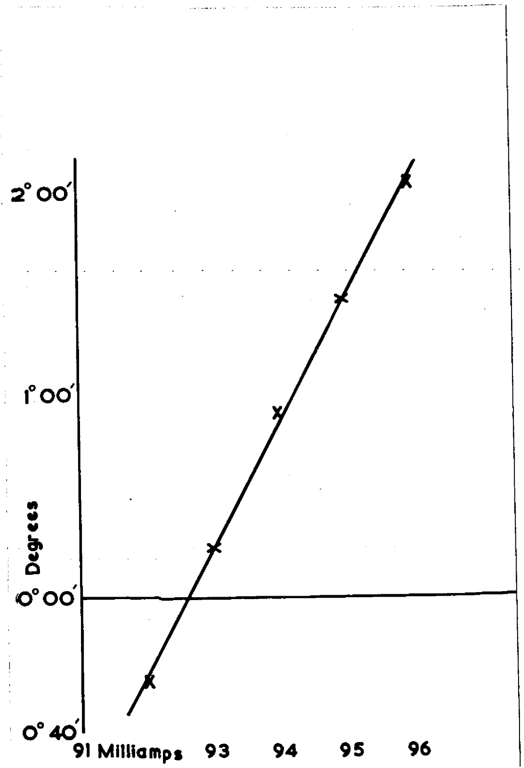


Fig. 2.4 Graph showing the current required in the V coils. Displacement of the dip needle from horizontal is plotted as ordinate, and current through the V coils as abscissae.

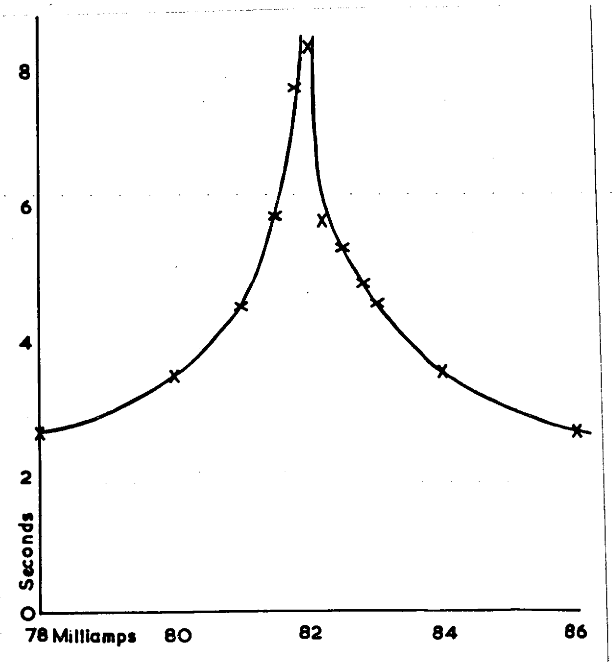


Fig. 2.5 Graph showing the current required in the N coils. The period of swing of a magnet suspended at the centre of the system is plotted as ordinate, and the current through the N coils as abscissae.

reversed on its pivot). For small values the variation with current is linear and the compensating current in the V coils (92.6m.A.) may be read off the graph (Figure 2.4).

The horizontal field was then tested by timing the swing of a magnet suspended at the centre of the coils. The period is inversly proportional to the restoring force, which is the resultant of the earth's horizontal component and the fields due to the N and E coils.

The current in one pair was kept constant while that in the pair to be balanced was altered by steps through a range in which the period of swing of the magnet passed through a maximum. Values of current against period are plotted in Figure 2.5. The curve separated into two symmetrical halves asymptotic to the required current strength.

The whole balancing process was divided into eight stages as follows:-

1. V coils balanced with no current in other coils.
2. N coils balanced with the current found in (1) in the V coils and no current in the E coils.
3. V coils balanced with the current found in (2) reversed in the N coils and no current in E coils. The optimum current was less than in (1), hence the N coils with a normal sense current had a component opposing the V coils. This was compensated by adding the difference in optimum V coil currents obtained in (3) and (1).

4. N coils balanced with new optimum current in V coils.
5. E coils balanced with currents in V and N coils those obtained in (3) and (4) respectively.
6. Repeated (3) with current in E coils found in (5).
7. Repeated (4) with current in E coils found in (5).
8. Repeated (5) with adjusted V and N currents found in (6) and (7). Stages (6), (7) and (8) were done after the work for the oven was completed to test for any movement of the coils during installation.

Thus the currents in the coils required to null the magnetic field in the centre of the oven were found to be:-

V coils - 92.6 m A.

N coils - 82.0 m A.

E coils - 0.5 m A.

The calculated and experimentally obtained values for the currents agree to 1.50% for the V coils and 0.84% for the N-S coils. This is good agreement, and shows the accuracy with which the coil systems have been made.

2.5 Detailed Testing of the Residual Field in the Oven. The field in the oven was now tested by measuring directions in test specimens heated in the oven and cooled with currents in the coils both less and more than those previously determined.

This method depends on the fact that specimens heated above the Curie Point of the contained magnetic minerals become demagnetized, and if they are then cooled in zero magnetic field the directions of magnetization will be random, whereas if there is a small residual field the directions will tend to be aligned along it. By taking direction cosines in the vertical, north and east directions of all the test specimens measured, giving each specimen unit weight, it is possible by the sign of the resultant in each direction to find whether the current in the coil pair tending to null the component of the earth's magnetic field in this direction is too great or too small.

In principle, since very small intensities can be measured, this method should yield results of high accuracy. In practice it was found that this accuracy was affected not only by statistical fluctuations in specimens but also by local disturbances due, in particular, to nearby traffic. The non-magnetic hut was built well removed from roads and buildings but during recent building construction heavy steel equipment has been working within 200 metres. This has probably limited the accuracy of the results.

Eight test runs were made in which 5, 6 or 7 specimens, placed with known orientation in various parts of the oven, were heated above 565°C, and cooled in a magnetic field that was the vector sum of that due to the currents in the coils shown in

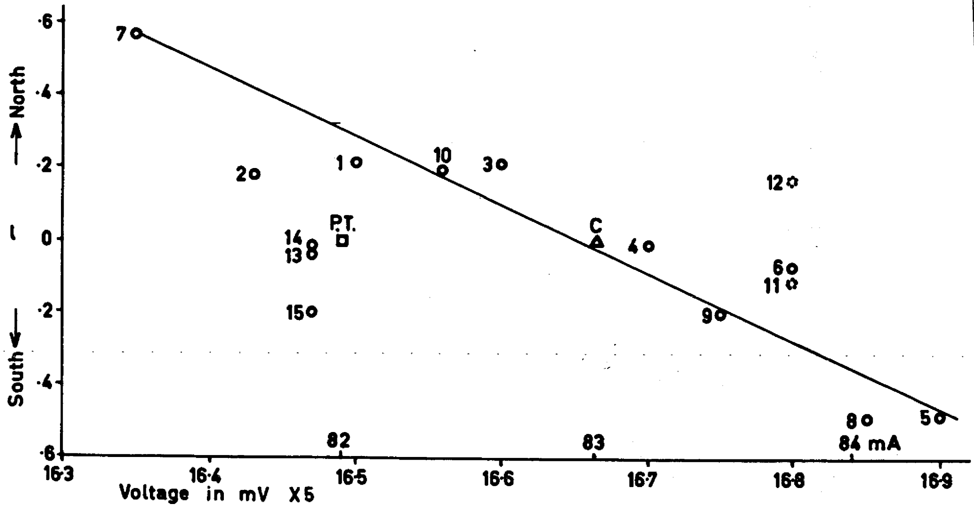


Fig. 2.6 Detailed testing of N coils. The mean north direction cosines (l) from heated specimens are plotted as ordinates against the back voltage due to the current through the N coils as abscissae. The current values obtained by calculation (△ C) and preliminary testing (□ P.T.) are also shown.

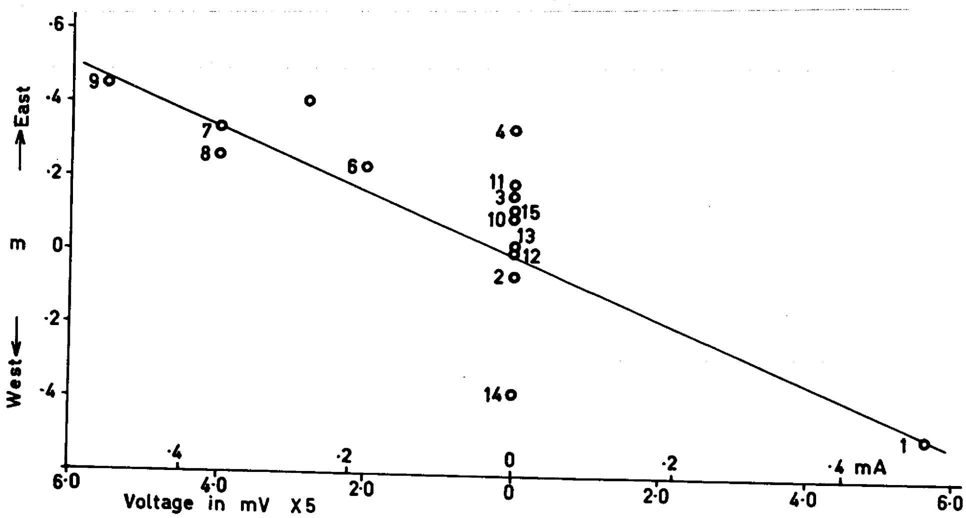


Fig. 2.7 Detailed testing of E coils. The mean east direction cosines (m) from heated specimens are plotted as ordinates against the back voltage due to the current through the E coils as abscissae.

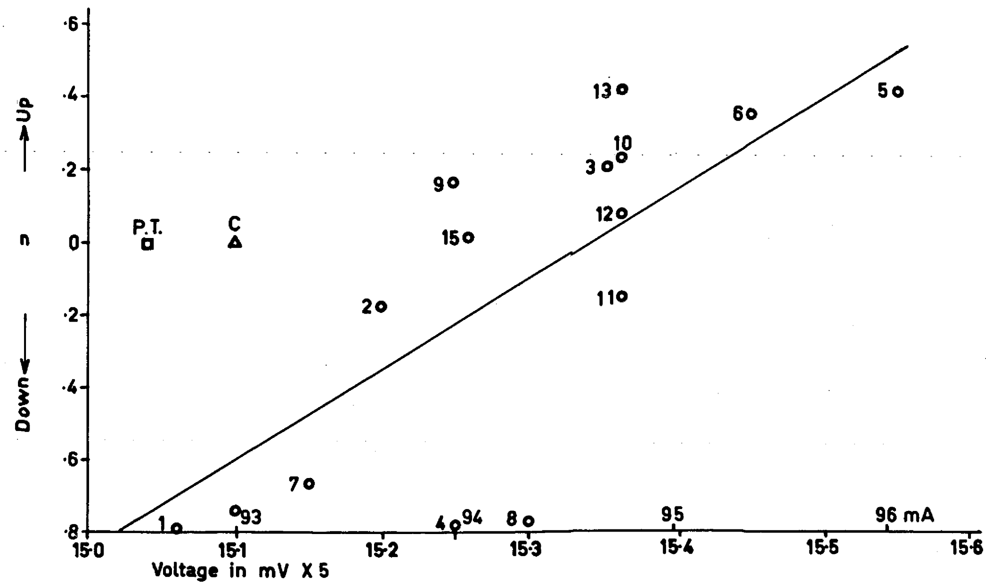


Fig. 2.8 Detailed testing of V coils. The mean upwards direction cosines (n) from heated specimens are plotted as ordinates against the back voltage due to the current through the V coils as abscissae. The current values obtained by calculation (△C) and preliminary testing (□P.T.) are also shown.

Table 2.3 and that of the earth. The back voltage from the currents in the coils was accurately measured with a potentiometer, and these voltages are plotted against the resultant of the direction cosines in the relevent direction in Figures 2.6, 2.7, and 2.8. The current to which the voltages correspond is also shown along the abscissa scale, and it may be seen that the currents required to null the earth's magnetic field agree with those found using the dip circle and swinging magnet to better than 2 per cent, although the scatter of points over the restricted range used is high.

Hence current values within 2 per cent of those found above were used in ensuing thermal experiments, approaching the true values by successive approximations, and whenever a set of specimens was heated above their Curie Points, direction cosines were obtained from them to give additional points 9 to 15 on Figures 2.6, 2.7, and 2.8, and Table 2.3.

Over the small range of field values covered by the experiments of which results are plotted in the figures the gradient of the curve of resultant direction cosine in a given direction plotted against the current producing a field in that direction should be constant, and the points lie on a straight line, whereas the scatter of points is quite large. The reasons for this scatter are thought to be:-

(1) Statistical scatter due to lack of randomization in small samples.

TABLE 2.3

TESTING FIELD FROM DEGAUSSING COILS BY DIRECTIONS IN SPECIMENS

Run	Date	Regional Magnetic Disturbance	Number of Specimens	Temp. Reached °C	Back Voltage from Coils X5 millivolts W	E	V
1	10. 6.60	V.Q.	7	600	16.50	5.64A	15.06
2	12. 8.60	S.S.	5	565	16.43	0	15.20
3	15. 9.60	V.Q.	5	565	16.60	0	15.35
4	16. 9.60	V.Q.	6	565	16.70	0	15.25
5	4.10.60	S.S.	6	590	16.90	2.80R	15.55
6	5.10.60	S	6	590	16.80	2.00R	15.45
7	6.10.60	B.S.	6	590	16.35	4.00R	15.15
8	7.10.60	B.S.	6	590	16.85	4.00R	15.30
9	3.11.60	S.S.	20	605	16.75	5.51R	15.25
10	24.11.60	M	24	600	16.56	0	15.36
11	5. 7.61	M	12	565	16.80*	0	15.36
12	7. 7.61	M	20	630	16.80*	0	15.36
13	14.11.61	-	23	675	16.47	0	15.36
14	13.12.61	-	26	600	16.47	0	15.10
15	25. 1.62	-	22	600	16.47	0	15.26

* Poor connection is N circuit makes value doubtful

V.Q. = Very Quiet, M = Moderate, S = storm,
B.S. = Bad storm, S.S. = Severe storm.

Current in Coils in Milliamps			Magnitude of Direction cosines of resultant of unit vectors		
W	E	V	l	m	n
82.0	0.5A	92.6	+.21	-.47	-.80
82.0	0	94.0	+.18	-.06	-.18
82.6	0	94.6	+.21	+.16	+.20
83.2	0	94.1	-.01	+.34	-.78
84.0	0.25	96.0	-.48	+.41	+.41
83.8	0.19	95.3	-.07	+.23	+.35
81.2	0.35	93.3	+.57	+.34	-.66
84.0	0.35	94.5	-.49	+.26	-.77
83.8	0.48	94.2	-.20	+.45	+.16
82.5	0	95.0	+.19	+.10	+.22
81.0*	0	95.0	-.11	+.19	-.16
81.5*	0	95.0	+.17	+.01	+.07
82.0	0	95.0	-.04	+.02	+.41
82.0	0	93.0	-.01	-.38	-.74
82.0	0	94.0	-.20	+.12	+.01

(2) Some residual NRM in some specimens which contain a mineral with a Curie Point above that of the temperature reached.

(3) Fluctuations of the earth's magnetic field due to magnetic storms. This source of error is probably negligible as there appears to be no correlation between magnetic storms observed at Toolangi, in Victoria, given qualitatively in Table 2.3, and anomalous results.

(4) Local fluctuations of field due to movement of iron objects and generation of large electric currents both within and outside the hut. The former were kept to a minimum during experiments and are considered to be negligible. The latter, due to building operations mentioned above, may have been a major source of error during some runs.

(5) Small fluctuations of current in the coils, due to voltage changes in the batteries and temperature changes in the coils, were kept to a minimum by frequent current adjustments. However there was a small reduction in the resistance of the coils after the insulating jacket was raised and the heat released: this caused a small increase in current, mainly in the N coils, at a time when the temperature of the specimens was falling through the Curie Point of their main magnetic constituent, which may have acquired a direction affected by this current.

2.11

(6) The direction cosines in the 3 mutually perpendicular directions are not entirely independent, and a large directed component in one direction reduces the size of the components in other directions. Hence when the current in the V and N coils were at extreme values away from that required to null the earth's magnetic field, the resultants in the other two directions were too small. This factor becomes negligible as the true nulling current is approached.

(7) In some cases the readings on the potentiometer and the ammeter did not correspond (see Table 2.3). In most cases differences were 0.1mA or less and due to the limit of accuracy with which the ammeter could be read, but the large discrepancy in the N coils readings for runs 11 and 12 were later found to be due to a faulty connection in the circuit and these values must be disregarded.

Despite the scatter of points the results indicate that the nulling current in the V coils is 94.6 ± 0.5mA and in the E coils 0 ± 0.4mA. A current of 0.5mA in the V coils represents a field of 290γ in the oven and a current of 0.4mA in the E coils represents a current of 20γ in the oven.

The first 10 runs indicate a current of $82.9 \pm .5$mA in the N coils. Minor repairs to the N electrical circuit, in which it was found that one joint had a high variable resistance, were then made. After repair the required nulling current was $81.9 \pm .5$mA. A current of 0.5mA in the N coils represents a field of 150γ in the oven. It appears that some small affect that increased the anulling current necessary in the N coils was removed at the time of repair, after which the null current agreed very closely with that found in the preliminary experiment (82.0mA).

To test the homogeneity of the field within the oven the direction cosines from the specimens of runs 9, 12, 13 and 14 were separated into vertical and horizontal layers at different distances from the centre, and the results of these are given in Table 2.4. Differences between directions from these layers and the resultant from all specimens is also given so that different runs can easily be compared. The number of specimens in each layer ranged from 6 to 12 so that considerable statistical variation will occur. It may be seen that in most cases these differences are less than 10 per cent. Differences over 10 per cent are underlined, and those over 20 per cent doubly underlined. It is clear from underlining on Table 2.4 that departures from the mean direction of all specimens occur at random, except that they are somewhat less frequent on the bottom layer, and in runs 13 and 14. This indicates that the magnetic field in the oven under operating conditions is homogeneous within the limits available from these experiments.

TABLE 2.4

TESTING MAGNETIC FIELD VARIATIONS WITHIN THE OVEN

		D	I	Dir.Cos.	Diff.
Run		9	9	9	9
Date				3.11.60	
Number of specimens				20	
Back Voltage in mV. x 5	N			16.75	
	E			5.51	
	V			15.25	
Current in Coils in M.A.	N			83.8	
	E			0.48	
	V			94.2	
Top	(N = l)	305	+35	+.14	-.02
	(E = m)			-.20	0
	(V = n)			+.57	+.12
Middle	(N = l)	298	+20	+.22	+.06
	(E = m)			-.43	-.23
	(V = n)			+.34	-.11
Bottom	(N = l)	38	+24	+.09	-.07
	(E = m)			+.08	+.28
	(V = n)			+.41	-.04
North	(N = l)	91	+34	-.01	-.17
	(E = m)			-.60	-.40
	(V = n)			+.55	+.10
South	(N = l)	319	+10	+.24	+.08
	(E = m)			-.21	-.01
	(V = n)			+.16	-.29
East	(N = l)	349	+27	+.29	+.13
	(E = m)			-.06	+.14
	(V = n)			+.46	+.01
West	(N = l)	72	+25	+.06	-.10
	(E = m)			+.20	+.40
	(V = n)			+.42	-.03
All Specimens	(N = l)	38	+24	+.16	
	(E = m)			-.20	
	(V = n)			+.45	

Diff. is the difference between the resultant from each layer and that from all the specimens.
*These values are unreliable due to a loose connection in the circuit.

12	12	13	13	14	14
7.7.61		14.11.61		13.12.61	
20		23		26	
16.80*		16.47		16.47	
0		0		0	
15.36		15.36		15.10	
81.5*		82.0		82.0	
0		0		0	
95.0		95.0		93.0	
Dir.Cos.	Diff.	Dir.Cos.	Diff.	Dir.Cos.	Diff.
+.14	+.07	-.07	-.03	-.04	-.03
+.02	-.15	-.06	-.08	-.59	-.21
-.13	-.14	+.31	-.10	-.67	+.07
-.19	-.26	+.18	+.22	+.17	+.18
+.01	-.06	+.19	+.17	-.33	+.05
+.22	+.21	+.22	-.19	-.83	-.09
+.07	0	-.04	0	-.01	0
+.17	0	+.02	0	-.38	0
+.01	0	+.41	0	-.74	0
+.36	+.29	-.07	-.03	-.09	-.08
+.35	+.18	+.11	+.09	-.33	+.05
-.03	-.04	+.32	-.09	-.62	+.12
-.29	-.36	-.13	-.09	-.05	-.04
+,24	+.07	+.04	+.02	-.33	+.05
+.17	+.16	+.55	+.14	-.83	-.09
+.10	+.03	-.16	-.12	+.11	+.12
+.10	-.07	-.02	-.04	-.30	+.08
+.48	+.47	+.54	+.13	-.81	-.07
.00	-.07	-.11	-.07	-.11	-.10
+.30	+.13	-.07	-.09	-.49	-.11
-.37	-.38	+.45	+.04	-.63	+.11
+.07		-.04		-.01	
+.17		+.02		-.38	
+.01		+.41		-.74	

2.6 Conclusions. The method of using randomization of directions of specimens in the oven to determine the currents necessary in the coils is very accurate, but it is sensitive to external influences. The difference between the current required in the V coils found experimentally using a dip circle (92.6mA), and using directions from specimens (94.6mA), is probably due both to scatter in the latter caused by local disturbances, and to sticking of the needle of the dip circle due to worn pivots. The agreement for the N coils is excellent. The square coils are very satisfactory in that they provide a homogeneous magnetic field of less than 100γ within the oven, provided operating conditions are suitable.

CHAPTER 3. RECONNAISSANCE SURVEYS.

3.1 Requirements. Although a reconnaissance survey does not materially add to the scientific results, it forms an essential preliminary since it is only after a survey of this type that rocks suitable for more detailed studies can be found.

To study the earth's magnetic field in a previous epoch from the direction of NRM of a rock body it is necessary to know as far as possible both the time of formation of the body and also that the measured direction of magnetization was that of the field at the time of formation. Both these requirements impose severe limitations on suitable rocks. The age restriction limits collection either to rocks in sedimentary sequences, or to rocks that may be dated by radio-isotope methods. The magnetization restriction eliminates all rocks, such as most limestones and many shales and granites, too weakly magnetized. Weathered rock also is unsuitable because of alteration of the ferrimagnetic minerals. Metamorphic rocks, too, should be avoided since we do not know the effect on magnetization directions of a complex stress history or the chemical changes that may have occurred at unknown times.

The suitability of rocks may be tested by experimental and statistical analysis of results. Most regions have been but little studied palaeomagnetically, so that it is necessary, when embarking on a study such as this, to collect from a wide variety of rock

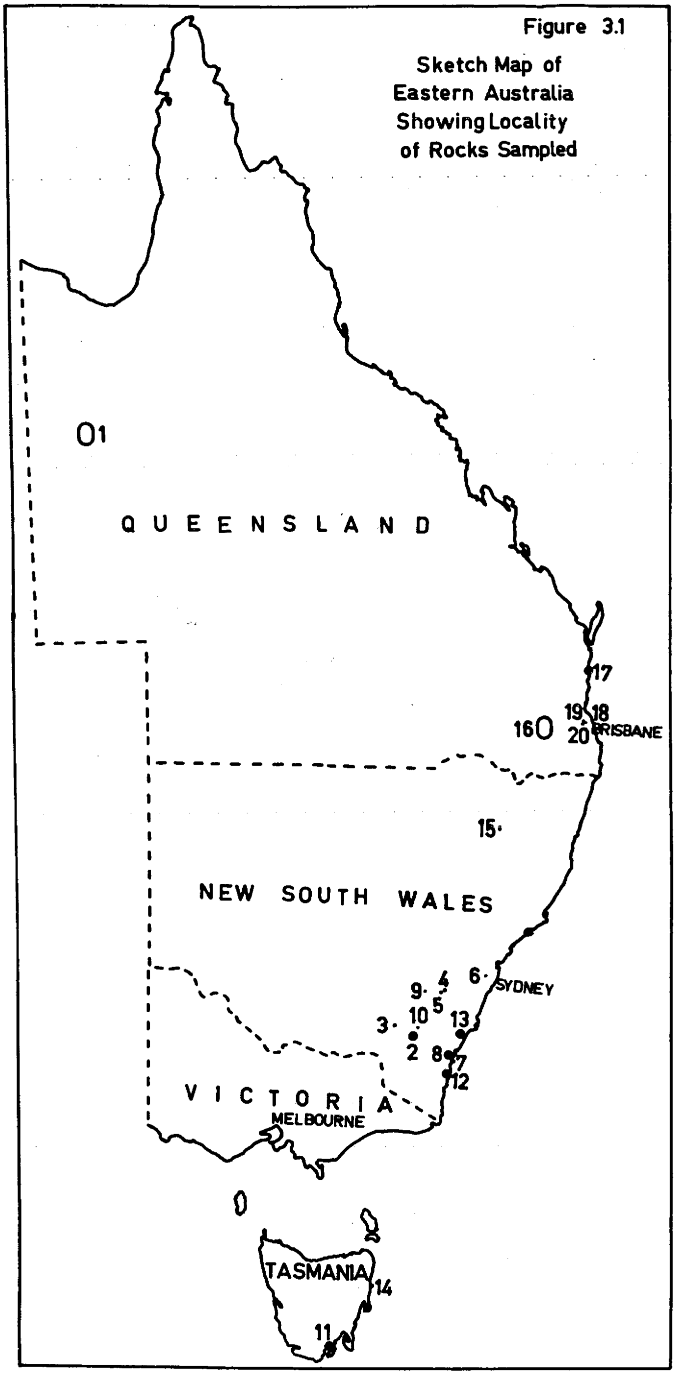


Figure 3.1

Sketch Map of Eastern Australia Showing Locality of Rocks Sampled bodies in order to obtain some knowledge of what are likely to be useful and interesting rock types. This was done and Figure 3.1 shows the locality of each rock body sampled. This chapter briefly describes the work that has been done in outline on rock bodies. Those studied in detail are described in the succeeding chapters.

3.2 Mount Isa Granites. Two or three oriented samples from numerous Pre-Cambrian granite masses that intrude the Pre-Cambrian belt that crops out between Duchess and the Nicholson River in Western Queensland were collected by a Bureau of Mineral Resources survey party collecting granite for age determination. The idea was to measure ages and magnetization directions from the same place. Directions from 113 specimens cut from these samples were measured, but the results were lost in the fire in the Cockcroft building of the Australian National University on July 6th 1960. From memory it can be said that very high intensities at some sites suggested lightening strikes (Graham 1961, Cox 1961), whereas the magnetization in some specimens was less than 10^{-7} e.m.u./cc and could not be measured. Directions of magnetization were widely scattered at all sites, and after the initial setback it was not considered worthwhile to treat them further.

3.3 Murrumbidgee Bathylith. This concordant granitic mass elongated meridionally has been examined by Snelling (1960) and divided into nine petrologically distinct phases. In common with most concordant granites its thermal and stress history may be complex, complicating the interpretation of palaeomagnetic results. Of 63 samples measured, taken from 11 sites in three petrological phases of the bathylith, 20 had intensities $<10^{-7}$ e.m.u./cc and could not be measured and 8 others had intensities at the lower limit of the range of our instrument. The directions obtained in the remaining samples gave low dips to the north-west, widely scattered about a direction that has been obtained from Devonian lavas and sediments nearby (Green 1959); they are stable in the present earth's field. These figures are taken from an annual report, as the results were burnt in the Cockcroft Building fire. Because of low intensities and scattered directions they were not pursued.

3.4 Felsite from Queensland University Mine. Three samples were collected from the 240ft. level of the mine where the vertical felsite dyke is 15 feet wide. The dyke contains silver-lead mineralization, believed to be a late stage in the consolidation of the felsite, and it was hoped to obtain a lead age from this. The felsite, however, appears to contain virtually no magnetic mineral, and the only specimen that deflected the magnetometer had an intensity of 0.5×10^{-6} e.m.u./cc so that the rock was not suitable for magnetic study.

3.5 Enogera Granite. Two specimens were cut from each of three samples taken from the granite aggregate quarry at St. John's Wood, a Brisbane suburb. The NRM directions, and also those after partial

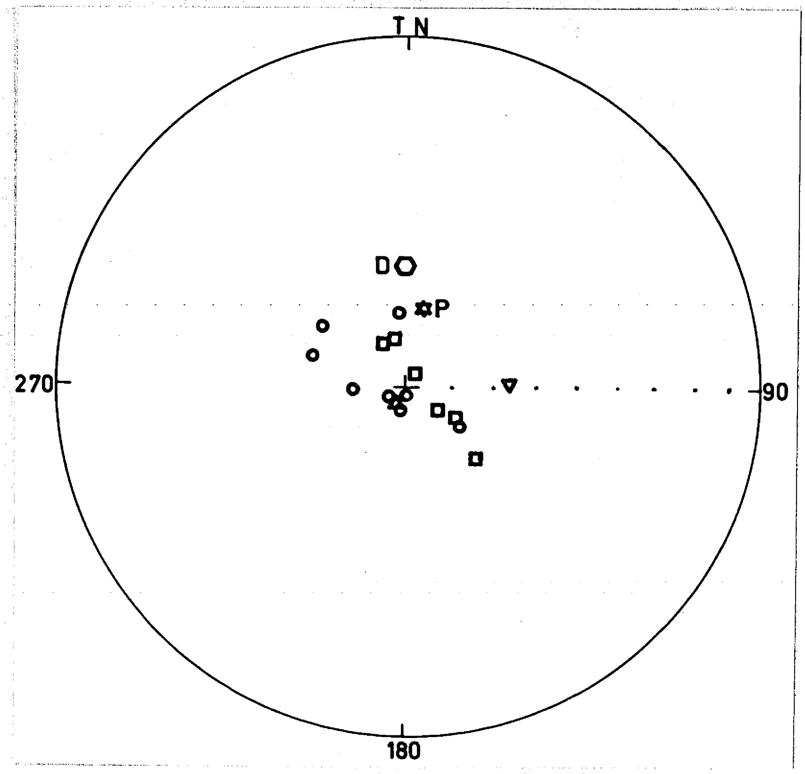


Fig. 3.2 Directions of remanent magnetization from the Coles Bay Granite. On this, and all subsequent figures, north-seeking directions are plotted as circles on the upper hemisphere and dots on the lower hemisphere of a Schmidt equal area projection. D denotes the dipole field direction, and P that of the present field. O=initial directions, □ =directions after magnetic cleaning in 150 oersteds, △ =directions after magnetic cleaning in 300 oersteds, and ▽ =directions after magnetic cleaning in 450 oersteds.

demagnetization in 150 and 300 oersteds alternating field, were random at P=0.05, (see Appendix 3.1) hence the rock was unsuitable for palaeomagnetic work.

3.6 Coles Bay Granite. Eight specimens cut from two samples of Coles Bay Granite, collected by P.M. Stott from a quarry on the north-east coast of Tasmania gave a tight group with steep negative inclination, that was not appreciably affected by magnetic cleaning in 150 oersteds (Figure 3.2). One specimen was subjected to alternating fields of 300 and 450 oersteds and changes both of direction and intensity remained small (see Appendix 3.2). This granite is considered on geological evidence to be of post-Silurian and pre-Permian, probably Devonian age (Walker 1957 and personal communication), whereas the directions of magnetization suggest a Mesozoic age. Could our specimens have been reheated by more recent dolerite? More samples from more sites would be necessary to test this possibility and inaccessibility from Canberra inhibited further collection. Unfortunately alteration of the biotite made K-Ar isotope age determination impossible (McDougall personal communication). These preliminary results, however, indicate that the magnetization is a stable one, and that more detailed palaeomagnetic sampling of this granite, perhaps in conjunction with total rock Rb-Sr age determination, would be well worth while.

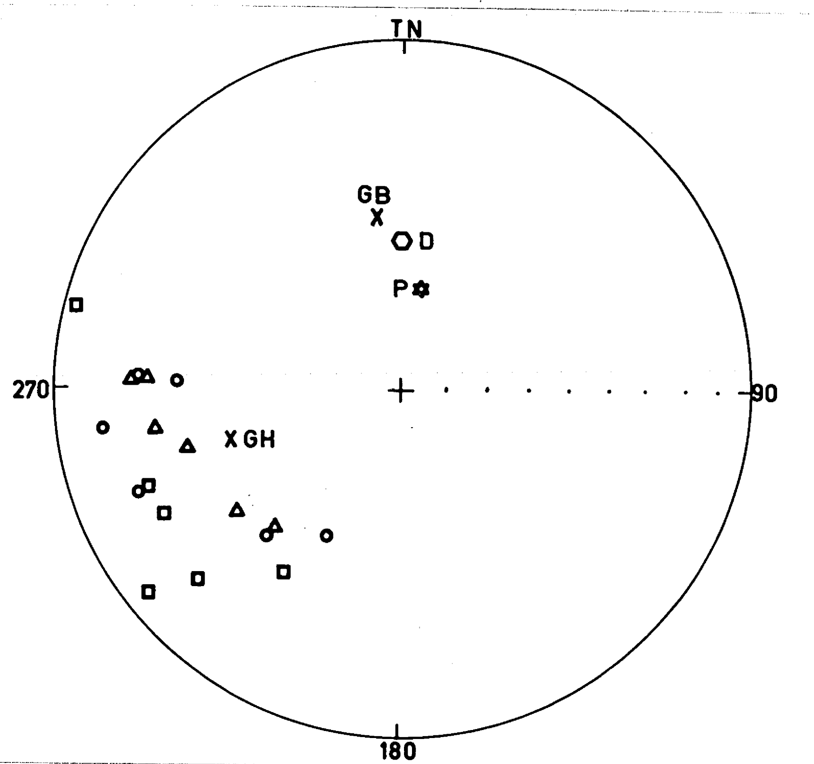


Fig. 3.3 Directions of remanent magnetization from the Painter Porphyry at Mount Stromlo. Conventions as in Fig. 3.2. GB denotes mean of Green's (1959) results with respect to the bedding, and GH represents the mean of his results with respect to the horizontal.

3.7 Painter Porphyry. Three samples were taken from the pit excavated near the summit of Mount Stromlo during the installation of a new instrument. The porphyry is of Upper Silurian or Lower Devonian age (Opik 1958), and has been sampled elsewhere by Green (1959). Its attitude in this locality is uncertain. The directions of NRM (Appendix 3.3) show a moderate scatter that is reduced by magnetic cleaning in 150 oersteds, and there is a further improvement in precision after treatment in 300 oersteds. The grouping after magnetic cleaning in 300 oersteds, in a direction well removed from that of the present field, suggests that this may be a stable direction, but the mean is some 70^{o} of arc away from Green's bedding wise mean, although it is much closer to his horizontal wise mean (Figure 3.3). In view of possible undetected movement after emplacement more work was not done on this body.

3.8 Murrumburrah Basic Rocks. Four samples from a quarry in a leucite basalt plug about a mile east of Murrumburrah, and two from the intruded granite, gave random NRM directions as shown in Appendix 3.4, and the directions remained random in the basalt specimens after magnetic cleaning in 75 and 150 oersteds. The basalt contained xenocrysts and xenoliths of eclogite, and it was hoped to put age limits on the intrusion from the magnetization directions, but unfortunately they proved unsuitable.

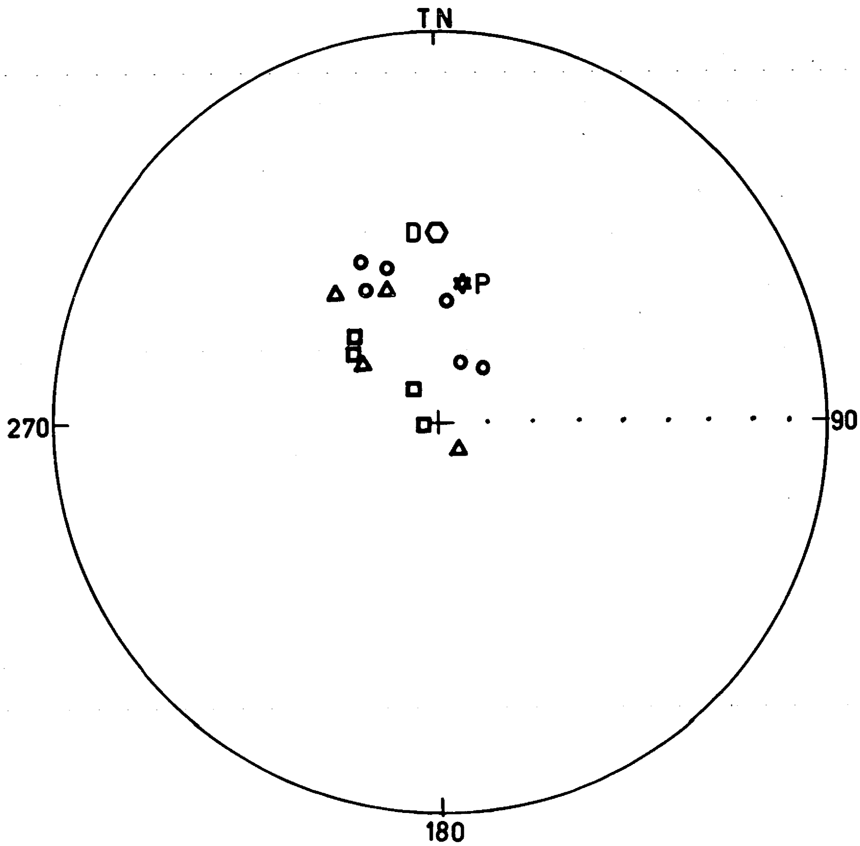


Fig. 3.4 Directions of remanent magnetization from the Ruby Hill basanite. Conventions as in Fig. 3.2.

3.9 Eucumbene-Tumut Tunnel and Cabramurra Basalts. Dr's Lovering and McDougall collected two oriented samples from the Snowy Mountains Scheme Eucumbene-Tumut Tunnel and two samples from the basalt quarry at Cabramurra. The NRM directions were lost in the fire previously alluded to but those from the tunnel were random and the directions from Cabramurra were widely scattered and it was not thought worth while to do stability work on them.

3.10 Ruby-Hill Basanite. Three samples taken by G. Halford from a basanite dyke cutting a breccia pipe 12 miles south of Bingera, were used to compare their characteristics during partial demagnetization in alternating magnetic fields with those from Mount Dromedary sites. The dyke contained eclogite and granulite inclusions and is of interest in mantle studies. The NRM directions (see Appendix 3.5 and Figure 3.4) were moderately scattered, and four specimens were partially demagnetized in successive alternating fields of 37, 75, 150, 225, 300 and 450 oersteds. Analysis of these directions (Table 3.1) showed that the least scatter occurred after treatment in a field of 150 oersteds. It is also evident that after cleaning in each higher field up to this value the mean direction is moved further away from the present and dipole field positions, whereas after cleaning in fields greater than 150 oersteds the mean direction is sensibly constant but the scatter increases. This is interpreted as being due to the removal of a secondary component that is sensibly removed by partial demagnetization in an alternating field of 150

TABLE 3.1

RUBY HILL ALTERNATING MAGNETIC FIELD CLEANING

of 4 Specimens at the 1S Level.

$H_p\sim$	D	I	R	a
0	350	-63	3.914	15.8
37	341	-70	3.926	14.6
75	332	-71	3.933	13.9
150	312	-75	3.942	12.9
225	314	-70	3.943	12.8
300	304	-77	3.921	15.1
450	327	-73	3.825	22.8

$Hp\sim$ is the peak value of the alternating magnetic field.

D is the declination measured clockwise from true North.

I is the inclination measured positively downwards from the horizontal plane.

R is the length of the resultant of the 4 unit vectors.

a is the semi-angle of the cone of confidence about the mean direction within which the true mean direction lies with a probability P = 0.95.

oersteds; in higher fields the primary component is also reduced to such an extent that random directions form a significant proportion of the direction measured. Thus these results suggest that minimum dispersion of directions from a group of specimens from the same site is a good criterian for the removal of secondary components. The pole position calculated from results after treatment in 150 oersteds is (49S., 190E.) and by comparison with pole positions from rocks of known age (see Figure 11.1) suggests a pre-Tertiary, possibly Mesozoic age.

3.11 Moruya Granodiorite including Kelly's Point. The Moruya granodiorite forms a north by west trending belt 5.6km wide with the township of Moruya near the centre. It is considered to be of Devonian age (Brown 1928). The intrusion consists of biotite-granite in the north, granodiorite in the centre, with diorite and gabbroic phases in the south-east. NRM directions, lost in the fire mentioned previously, from 2 sites in the granodiorite, a building-stone quarry 2 miles east-north-east of Moruya, and a road cutting 3 miles south-south-east of the township, gave random directions and these sites are not considered further.

At Kelly's Point, the most easterly outcrop of the belt, gabbroic and tonalitic phases have been intruded by 6 dykes. In places the phases have sharp boundaries, but elsewhere there is hybridization. NRM directions from 20 samples taken from each dyke, the gabbroic, tonalitic and hybrid zones were lost in the

Cockcroft Building fire. Remeasurement showed that most of these were widely scattered, see Appendix 3.6, but directions from two of the basalt dykes were close to the present field, and one dyke, which contained garnet, pyroxene, and basic felspar inclusions, gave a direction with low dips to the north-west, which suggest a pre-Tertiary, possibly Devonian age. The results are suggestive of partial stability, so that specimens might well respond to magnetic cleaning, a treatment inhibited by lack of time.

3.12 Further Rock Bodies Sampled and Later Studied in Detail. The Mount Dromedary intrusive complex comprises a wide petrological variety of plutonic and hypabyssal rocks, and sediments baked by the intrusions, which display a wide range of magnetic properties. The stability of the magnetization directions from these rocks have been tested both by alternating magnetic field and thermal means, and these methods have been compared in chapter 4. This comparison is considered to support the validity of stability tests and cleaning techniques performed on other rocks.

Specimens collected by Boesen from the Gingenbullen Dolerite, the Prospect Dolerite and the Gibraltar Syenite, 3 small intrusive bodies in New South Wales, I tested for stability and the results are given in chapter 7.

The stability of the palaeomagnetic directions of the Monzonite Porphyry at Milton, in New South Wales, the intrusive complex at Noosa Heads in Queensland, and the Cygnet Alkaline Complex in

Tasmania are discussed in chapters 6, 8 and 9 respectively. These rocks, as also those from Mount Dromedary and the 3 intrusive bodies mentioned above, contain minerals suitable for K-A isotope age determination. The Brisbane Tuff has good stratigraphic control, and its magnetization forms the subject matter of chapter 5.

The age of the Tertiary igneous rocks of south-east Queensland is not accurately known, and an attempt is made in chapter 10 to relate the directions from extrusive and intrusive groups with those of Tertiary volcanic rocks of known age in Victoria, and hence improve our knowledge of the age relationships of the Queensland rocks, which it has not been possible to do by any other means.

Fig. 4.1 Looking east from near summit of Mount Dromedary, showing the surface expression of the rock types.

CHAPTER 4. MOUNT DROMEDARY INTRUSIVE COMPLEX

4.1 Introduction. Detailed palaeomagnetic work was done on rocks from Mount Dromedary for 2 reasons. Firstly the rock was comprehensively dated by K-A radio-isotope methods and proved to have formed in an epoch from which results are scarce and in which interest is high (see chapter 11), so that a precise result is of great value. Secondly the wide variety of rock types was very suitable for testing the various laboratory techniques, enabling the use of them on specimens from other rock bodies with greater discrimination.

4.2 Geology. The igneous rocks of the Mount Dromedary region, on the New South Wales coast 380km by road south of Sydney, are intrusive into isoclinally folded Lower Palaeozoic sediments. Brown (1930) tentatively concluded that the intrusion had a laccolithic form and that the variety of rock types was formed by differentiation *in situ*. The plutonic rocks range from adamellite, through monzonite and shonkinite to pyroxenite and associated with them are dykes of aplite, lamprophyre and dolerite. Figure 4.1 shows the topography formed by the intrusion, which yields rich dairy country in contrast to the sparsely populated sediments. The intruded sediments have been affected by the intruding material both by thermal and metasomatic alteration. A recent suggestion by Joplin (1962) has modified Brown's interpretation, but there is no evidence of tilting since emplacement. Results of petrological

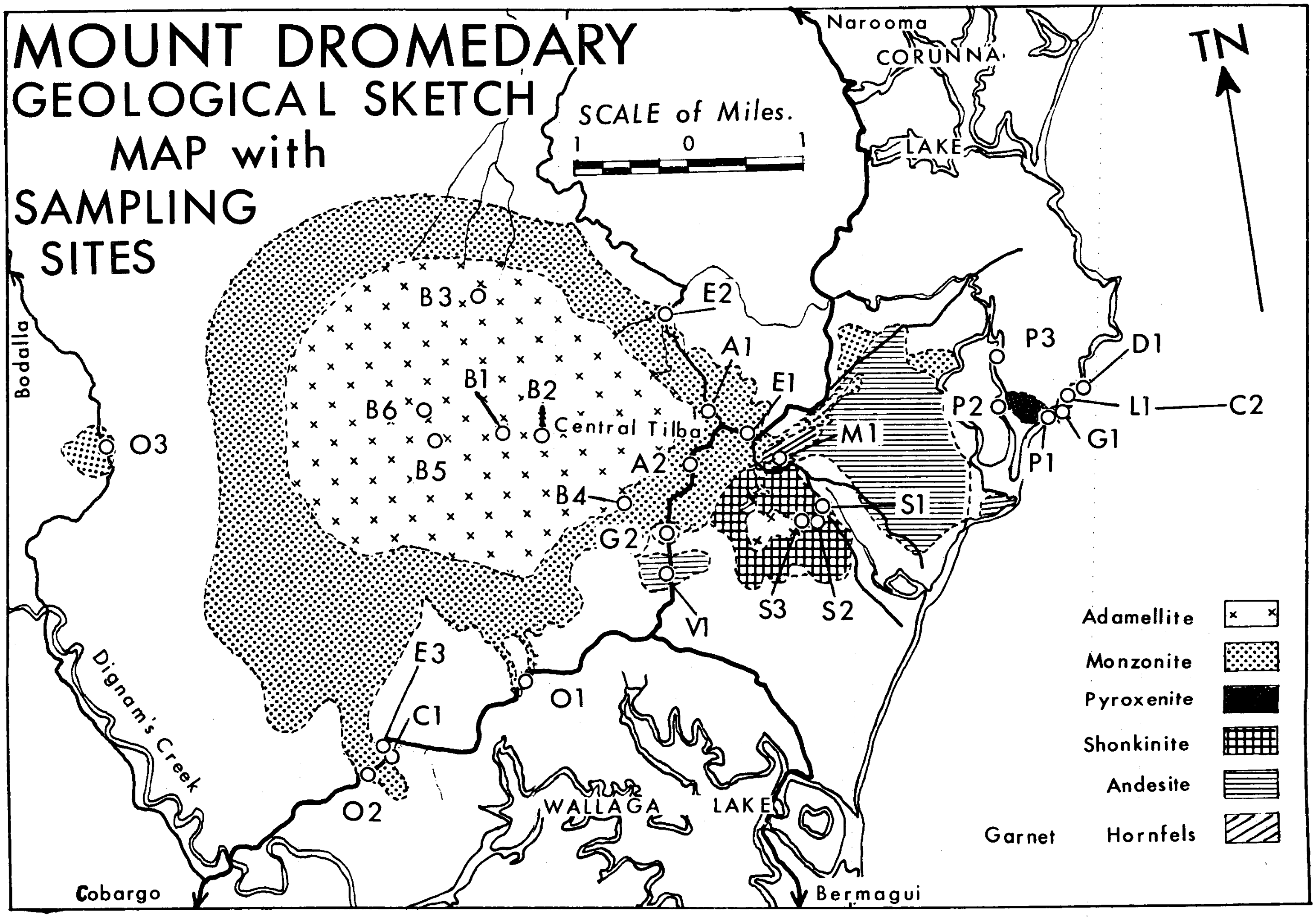


Fig. 4.2 Geological sketch map of Mount Dromedary, showing sampling sites. Map and geology modified after Ida A. Brown.

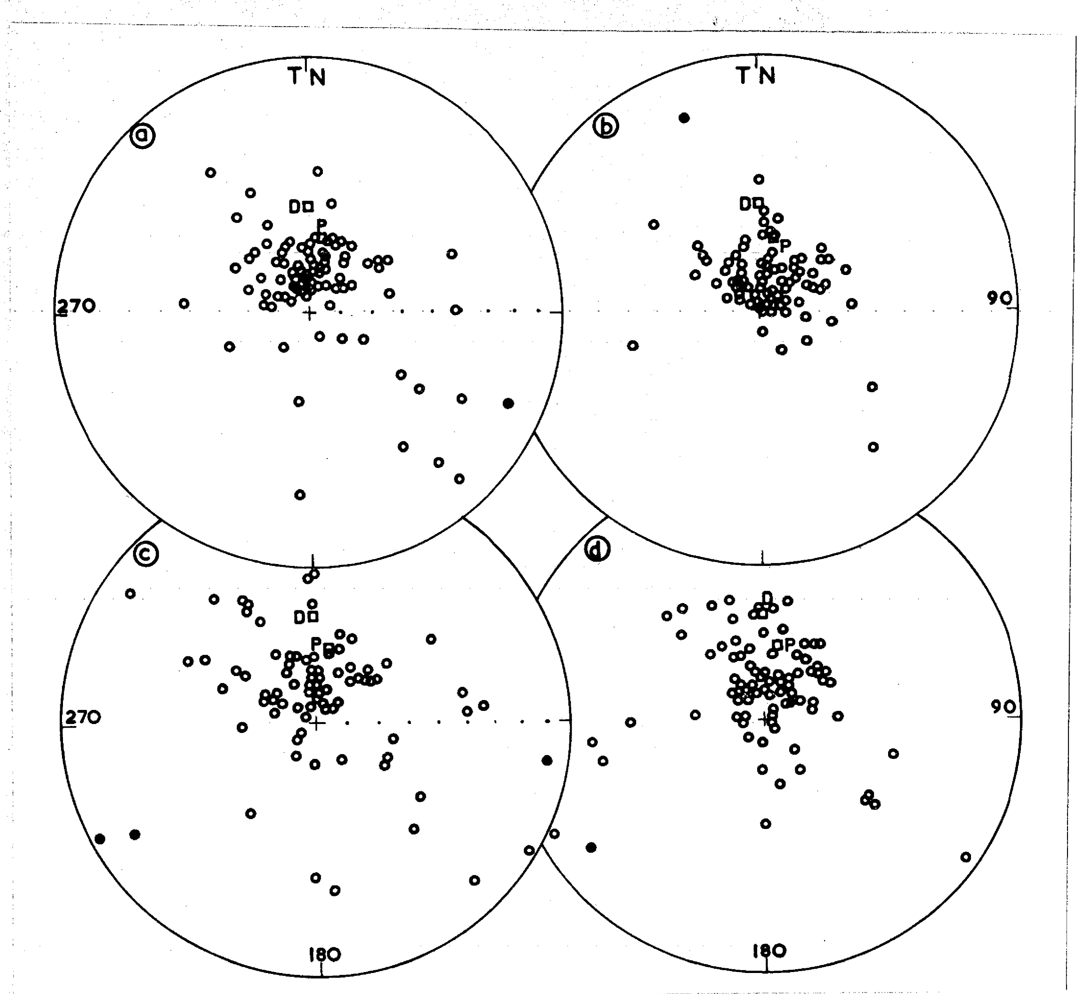


Fig. 4.3 Directions of remanent magnetization from Mount Dromedary. North-seeking directions are plotted as open circles on the upper hemisphere, and dots on the lower hemisphere of a Schmidt equal area projection. The present (P) and dipole (D) field directions are given. Diagrams (a) and (c) show the initial directions from specimens that were later treated by alternating magnetic fields and by heating respectively yielding the directions of diagrams (b) and (d).

examination of thin sections from each sampling site are given in Appendix 4.5.

The age of the intrusion was considered to be Permian on the grounds that the rocks were petrologically related to lavas of known Permian age further north on the Illawarra coast. More recently K-A isotope age determinations on biotites (Evernden and Richards 1962), hornblende and pyroxene from monzonite, shonkinite and pyroxenite gave a small scatter about 90 m.y. which places the intrusion at the top of the Cenomanian, in the upper part of the Lower Cretaceous Period. Samples were obtained from the major rock types and from the country rock heated by their intrusion. Sampling sites are shown on the geological sketch map of Figure 4.2 (modified after I. Brown).

4.3 Sampling and Results. Oriented samples were collected from 28 sites. At 3 sites (B1, B2 and B6) the directions of NRM were random and remained random after partial demagnetization. At sites B4 and G2 only one sample could be obtained and they are not considered further. The directions at site E1 were reversed and showed curious magnetic properties which are described in section 4.8. Results from the remaining 22 sites are listed in Table 4.1 and specimen directions plotted in Figure 4.3. The sites have been grouped into rock types using Brown's units supplemented by petrological examination of thin sections from each site.

TABLE 4.1

MOUNT DROMEDARY SITE DIRECTIONS AND INTENSITIES

LOCATION Rock Type	Site	S	N	M_n D	I	R	M_o
Adamellite (Banatite)	B3	3	4	240	-81	3.83	.44
		3	4	304	-80	3.85	.31
	B5	3	4	109	-45	3.78	.23
		3	4	106	-44	3.43	.17
Coarse Monzonite	A1	3	4	13	-70	3.96	1.6
		2	2*	142	-53	1.93	1.1
	A2	2	4	330	-80	3.81	.85
		2	4	320	-67	3.94	.58
Even Monzonite	E2	3	4	330	-47	3.94	.20
		3	4	328	-43	3.99	.24
	E3	2	4	351	-69	3.96	2.7
		2	4	347	-69	3.96	2.8
Olivine Monzonite	O1	2	4	9	-74	3.98	2.8
		2	4	25	-72	3.93	2.9
	O2	2	4	342	-72	3.81	2.3
		2	4	341	-62	3.77	4.2
	O3	2	4	13	-70	3.98	5.1
		1	2	33	-69	1.99	5.6
Gabbro	G1	3	4	24	-82	3.96	5.5
		2	4	22	-84	3.99	7.2
Shonkinite	S1	3	4	66	-25	1.57	.74
		3	4	146	-23	3.25	.96
	S2	4	8	252	-83	6.59	2.2
		4	4	248	-59	2.99	2.2
	S3	2	4	56	-62	3.99	.46
		4	4	303	-69	2.38	.46

TREATMENT		M_{TR} D	I	R	$\frac{M}{M_o}$
A.F.	300	89	-85	3.82	.09
TH.	465	282	-59	3.57	.32
A.F.	150	118	-62	3.54	.17
TH.	450	126	-39	3.58	.38
A.F.	225	12	-69	3.95	.27
TH.	380	134	-70	3.68	.38
A.F.	225	27	-78	3.95	.13
TH.	305	340	-68	3.89	.66
A.F.	225	35	-64	2.66	.29
TH.	201	326	-50	3.93	.81
A.F.	225	338	-74	3.95	.18
TH.	256	339	-77	3.97	.74
A.F.	75	23	-79	3.98	.57
TH.	380	33	-80	3.95	.82
A.F.	150	348	-78	3.89	.23
TH.	256	351	-78	3.91	.48
A.F.	225	77	-82	3.99	.19
TH.	450	26	-83	1.99	1.03
A.F.	150	3	-77	3.98	.24
TH.	380	42	-80	3.99	.80
A.F.	225	2	-75	3.93	.20
TH.	490	122	-60	3.52	.42
A.F.	150	349	-83	7.74	.11
TH.	450	245	-74	3.24	.49
A.F.	450	65	-70	3.99	.18
TH.	450	284	-78	3.44	.32

TABLE 4.1 continued

LOCATION				$\underline{M}_n$			$\underline{M}_o$
Rock Type	Site	$\underline{S}$	$\underline{N}$	$\underline{D}$	$\underline{I}$	$\underline{R}$	
Pyroxenite	P1	3	4	95	-87	3.50	6.2
		3	4	89	-55	3.43	12.0
	P2	2	4	229	-83	3.83	2.3
		2	4	272	-76	3.67	1.7
	P3	4	8	32	-71	7.90	2.4
		4	4	345	-66	3.37	2.6
Lamprophyre	L1	2	2	333	-76	1.98	2.6
		2	4	353	-79	3.93	2.1
Porphyry	D1	2	4	316	-66	3.75	.06
		2	4	354	-57	3.89	.04
Baked Contacts	C1	2	4	350	-80	3.99	3.0
		2	4	357	-78	3.99	4.3
	C2	2	4	65	-85	3.62	.49
		2	4	285	-81	3.94	.65
Garnet Hornfels	M1	2	4	342	-78	3.95	.04
		2	4	313	-82	3.94	.05
Andesite	V1	2	4	43	-72	3.98	3.2
		3	4	47	-73	3.90	2.4

$\underline{M}_n$, $\underline{S}$, $\underline{N}$, $\underline{D}$, $\underline{I}$, $\underline{R}$ and $\frac{M}{M_o}$ have the usual meaning. M_o is the average intensity in e.m.u./cc x 10^{-3}. M_{TR} specifies results after partial demagnetization. A.F. is the alternating magnetic field in oersteds. TH. is the temperature in ^oC to which the specimens were raised.

TREATMENT		M_{TR}			
		D	I	R	$\frac{M}{M_o}$
A.F.	225	338	-74	3.92	.22
TH.	340	33	-61	3.93	.42
A.F.	75	8	-84	3.97	.40
TH.	256	104	-85	3.90	.78
A.F.	300	30	-74	6.97	.27
TH.	450	40	-75	3.96	.67
A.F.	225	22	-68	1.84	.09
TH.	230	22	-79	3.92	.67
A.F.	75	308	-66	3.55	.24
TH.	201	356	-60	3.97	.62
A.F.	225	339	-79	3.99	.39
TH.	340	353	-78	3.99	.63
A.F.	225	50	-80	3.88	.29
TH.	256	333	-74	3.92	.43
A.F.	150	297	-84	3.94	.67
TH.	230	355	-88	3.77	.78
A.F.	300	46	-72	3.99	.63
TH.	305	46	-72	3.97	.87

* The NRM from only 1 specimen from each sample was measured, whereas the results after heating are from 4 specimens, two from each sample.

Because of the possibility of surface effects (such as incipient weathering or temperature hysteresis) changing the magnetization it was thought desirable to obtain samples from holes blasted by gelignite. The effect of blasting was tested at sites P3, S2 and S3. Two samples judged by eye to be unweathered and later confirmed by examination of thin section, were taken from the surface at these sites, and 2 samples from the bottom of a hole blasted later at the same place. Comparison of the results is made in Table 4.2. The test shows: (1) the NRM directions are more internally consistent from samples taken from the bottom of blast holes, than those from surface samples from the same sites.
(2) at site P3 there is no significant difference in direction or intensity either before or after partial demagnetization in alternating fields between surface samples and samples from blast holes.
(3) at sites S2 and S3 initial directions from surface samples were scattered, but after partial demagnetization in alternating fields, directions from these samples moved towards the direction of samples from blast holes, which remained constant and precise after treatment in alternating fields ranging from 150 to 450 oersteds.

<u>4.4 Alternating Magnetic Field Demagnetization</u>. From each of 11 sites representing all petrological groups 4 specimens were treated in an alternating magnetic field increased in steps up to 750 oersteds or until the scatter increased (Irving, Stott and Ward, 1961). Curves of precision (log *k*) and normalized intensity

TABLE 4.2

A TEST ON THE EFFECT OF BLASTING

				Surface Specimens				Specimens from Blast Holes			
Site	A.F.	S	N	D	I	R	M	D	I	R	M
P3	0	2	4	26	-71	3.98	2.2	42	-72	3.93	2.6
P3	150	2	4	37	-72	3.91	1.0	35	-75	3.99	1.1
P3	300	2	4	27	-76	3.98	.61	32	-75	3.98	.71
P3	450	2	4	39	-78	3.98	.38	48	-77	3.98	.50
S2	0	2	4	229	-46	2.39	2.87	17	-76	3.98	1.5
S2	150	2	4	348	-81	3.78	.28	352	-85	3.97	.22
S2	300	2	4	358	-74	3.84	.12	221	-83	3.62	.08
S3	0	2	4	269	-36	3.23	.37	56	-62	3.99	.54
S3	75	2	4	272	-33	2.87	.23	59	-67	3.98	.35
S3	150	2	4	275	-43	2.93	.16	83	-70	3.96	.26
S3	225	2	4	286	-55	2.96	.11	83	-70	3.96	.21
S3	300	2	4	291	-60	3.10	.11	78	-70	3.97	.17
S3	450	2	4	265	-63	3.28	.06	65	-70	3.99	.11

S, N, D, I, and R have the usual meaning. A.F. is the peak value in oersteds of the alternating magnetic field. M is the average intensity of magnetization of the group x 10^{-3} e.m.u./cc.

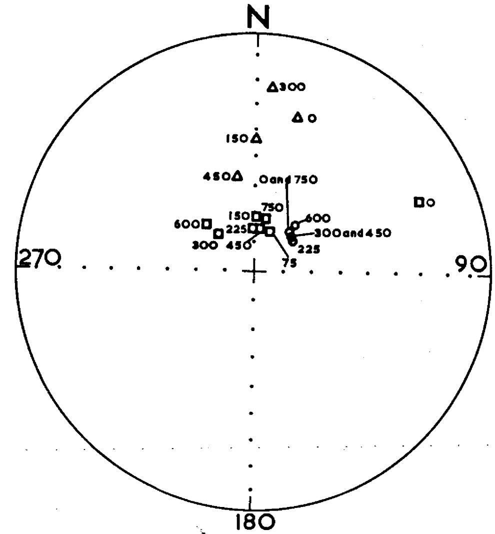


Fig. 4.4 <u>Mean directions after partial alternating field demagnetization at some Mount Dromedary sites.</u> The numbers indicate the peak field in oersteds applied to the specimens. O = site V1, □ = site S1, △ = site B6, Conventions as for Fig. 4.3.

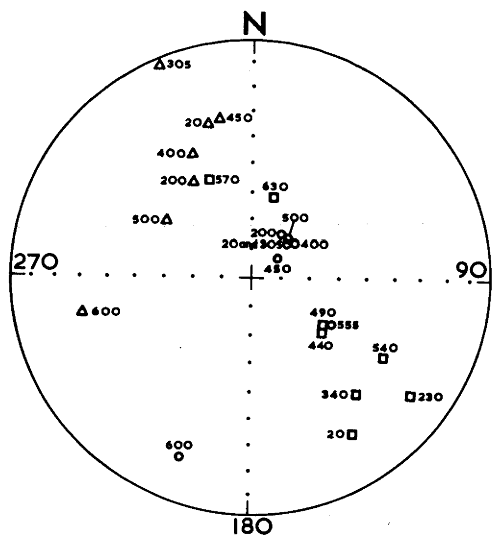


Fig. 4.5 <u>Mean directions after partial thermal demagnetization at some Mount Dromedary sites.</u> The numbers indicate the temperature in ^{o}C to which the specimens were raised. O = site V1, □ = site S1, △ = site B6, Conventions as for Fig. 4.3.

($\underline{M}/\underline{M}_o$) (Figure 4.6a and b) were plotted against alternating magnetic fields and a selection is represented in Figures 7a and b, and the results are given in Table 4.3. The estimate of precision, being based on only 4 specimens, is subject to considerable statistical fluctuations: the difference between the NRM precision for 2 sets from the same site (Table 4.1) which are later partially demagnetized indicates the magnitude of these fluctuations. Mean directions for representative sites at the fields stated are shown in Figure 4.4.

The specimens from Mount Dromedary demagnetized in alternating magnetic fields fall into the following 4 groups:

(1) At sites B1, B2 and B6 random directions remain random throughout demagnetization, and the intensity falls off rapidly at first, and then falls to a low fluctuating value.

(2) At sites S1 and P2 widely scattered or random directions become tightly grouped after partial demagnetization in alternating fields and scatter in higher fields, and the intensity falls off rapidly at first, and then steadily.

(3) At sites O1, O2, O3 and S2, the directions are tightly grouped, and the precision remains nearly constant until it decreases steadily. Intensity in low fields falls slightly less rapidly than group (2), but is otherwise similar.

(4) At sites M1 and V1 the directions are tightly grouped, and remain so over a wide range of demagnetizing fields. The intensity of this group falls off much more slowly.

TABLE 4.3

Alternating Field

Field in Oersteds	D	I	R	log k	$\frac{M}{M_o}$
Site B3					
0	240	-81	3.83	1.25	-
75	227	-75	3.67	0.95	.31
150	294	-88	3.78	1.12	.20
225	302	-88	3.74	1.06	.10
300	89	-85	3.82	1.22	.09
450	103	-71	2.65	0.34	.07
600	129	-68	2.43	0.28	.09
Site B6					
0	15	-33	2.96	0.46	-
150	0	-43	2.67	0.36	.16
300	5	-23	2.66	0.34	.11
450	349	-56	2.26	0.23	.07
Site A2					
0	330	-80	3.81	1.20	-
75	298	-78	3.95	1.75	.44
150	10	-79	3.94	1.73	.24
225	27	-78	3.95	1.77	.13
300	75	-73	3.89	1.44	.10
450	105	-82	3.78	1.14	.07
600	38	-74	3.85	1.29	.06
750	136	-78	3.94	1.71	.05

MOUNT DROMEDARY DEMAGNETIZATION

Site Means of 4 Specimens

Thermal

Temp. °C.	D	I	R	log k	$\frac{M}{M_o}$
20	304	-80	3.85	1.31	-
215	284	-78	2.44	0.28	.60
390	322	-70	3.27	0.61	.44
465	282	-59	3.57	0.85	.32
555	352	-68	3.30	0.63	.19
600	39	-47	2.70	0.82	.13
20	344	-33	2.41	0.28	-
200	329	-51	2.33	0.26	.38
305	336	- 3	2.08	0.20	.36
400	334	-42	1.20	0.04	.25
450	349	-32	2.43	0.28	.23
495	304	-55	1.18	0.04	.22
600	257	-30	2.08	0.20	.13
20	320	-67	3.94	1.68	-
200	347	-64	3.57	0.84	.66
305	340	-68	3.89	1.45	.65
400	353	-71	3.88	1.38	.50
495	339	-66	3.95	1.81	.37
555	238	-52	3.17	0.56	.05
600	232	-11	2.61	-	.05

TABLE 4.3 continued

Site E1					
0	210	+70	3.90	1.49	-
225	347	-55	2.22	0.23	.03
300	228	-60	3.13	0.53	.03
450	167	-74	2.99	0.48	.02
Site O1					
0	9	-74	3.98	2.26	-
75	23	-79	3.98	2.20	.57
150	34	-77	3.96	1.90	.21
225	4	-71	3.94	1.73	.11
300	4	-74	3.86	1.31	.08
450	27	-81	3.74	1.05	.07
600	41	-47	3.16	0.56	.04
Site D1					
0	316	-66	3.75	1.08	-
75	308	-66	3.55	0.83	.24
150	325	-62	2.70	0.36	.20
225	332	-26	1.93	0.15	.13
Site G1					
0	24	-82	3.96	1.89	-
150	3	-77	3.98	2.26	.24
225	349	-78	3.96	1.87	.21
300	355	-75	3.96	1.86	.18

20	202	+72	3.88	1.37	-
230	202	+72	3.91	1.52	.48
340	194	+48	3.24	0.60	.06
440	265	+67	1.00	0.00	.03
490	306	-23	1.88	0.15	.03
540	29	-43	2.54	0.30	.01
570	189	+17	0.93	0.00	.01
20	25	-72	3.93	1.66	-
230	21	-79	3.94	1.73	.90
380	33	-80	3.95	1.78	.82
480	21	-76	3.92	1.60	.64
530	55	-78	3.93	1.63	.64
550	21	-63	3.13	0.54	.39
570	41	-46	3.01	0.48	.26
20	354	-57	3.89	1.45	-
200	356	-60	3.97	2.00	.62
305	51	-58	3.50	0.78	.20
400	131	+ 4	2.60	0.32	.25
450	166	+ 4	1.99	0.18	.22
600	143	-11	1.75	0.11	.54
20	22	-84	3.99	2.58	-
230	16	-83	3.99	2.61	.91
380	42	-80	3.99	2.69	.80
480	35	-81	3.96	1.91	.69
530	20	-86	3.91	1.54	.66
550	307	-81	2.09	0.20	.33
570	100	-52	2.97	0.46	.05
600	9	-82	3.08	0.51	.05

TABLE 4.3 continued

Site P2					
0	229	-83	3.83	1.24	-
75	8	-84	3.97	2.02	.40
150	151	-87	3.95	1.75	.26
225	249	-87	3.87	1.35	.21
300	31	-87	3.96	1.83	.20
450	152	-83	3.97	1.94	.14
600	95	-76	3.80	1.18	.11
750	76	-79	3.76	1.09	.09
Site S1					
0	66	-25	1.57	0.08	-
75	20	-75	3.72	1.03	.26
150	2	-71	3.77	1.11	.22
225	2	-75	3.93	1.65	.20
300	315	-72	3.92	1.56	.14
450	5	-75	3.92	1.56	.10
600	314	-67	3.89	1.45	.09
750	11	-71	3.79	1.15	-
Site M1					
0	342	-78	3.96	1.82	-
75	333	-83	3.91	1.51	.74
150	297	-84	3.94	1.71	.74
225	337	-80	3.93	1.61	.67
300	15	-85	3.93	1.61	.67
450	335	-85	3.92	1.57	.62
600	317	-85	3.92	1.58	.60
750	344	-88	3.94	1.71	.59

Site P1					
20	89	-55	3.43	0.72	-
230	50	-68	3.71	1.02	.54
340	33	-61	3.93	1.65	.42
440	24	-81	3.84	1.41	.37
490	18	-73	3.91	1.52	.37
540	299	-55	3.08	0.51	.20
570	288	-56	2.11	0.20	.08
20	146	-23	3.25	0.60	-
230	126	-18	3.29	0.62	.67
340	137	-34	3.09	0.52	.43
440	127	-59	3.39	0.69	.44
490	122	-60	3.52	0.80	.42
540	121	-35	2.54	0.30	.19
570	336	-53	2.31	0.26	.04
630	15	-61	3.63	0.91	.05
20	313	-82	3.94	1.67	-
230	355	-88	3.77	1.11	.78
380	58	-78	2.66	0.34	.04
480	180	-59	1.80	0.15	.03

TABLE 4.3 continued

Site V1					
0	43	-72	3.98	2.12	-
225	50	-73	3.99	2.29	.70
300	46	-72	3.99	3.07	.63
450	47	-72	3.99	2.42	.55
600	41	-69	3.99	2.36	.43
750	44	-72	3.99	2.48	.35

20	47	-73	3.90	1.47	-
200	36	-72	3.93	1.65	.94
305	46	-72	3.97	1.94	.87
400	51	-71	3.92	1.59	.87
450	54	-79	3.94	1.68	.86
495	43	-72	3.95	1.76	.84
555	120	-58	1.98	0.18	.33
600	200	-20	1.98	0.18	.03

These groups, which grade into one another, may be explained on the relative coercivity of primary (O) and secondary (L) components as outlined in section 1.6. In group (1) O is entirely masked or obliterated by L. L in (2) is large in magnitude but has a low coercivity and is preferentially removed by the alternating magnetic field. In group (3) there is a negligible L and the gradient of the precision curve is a function of the coercivity of O. Group (4), ideal for palaeomagnetic work, is similar to group (3) but O has a higher coercivity.

The normalized intensity curves are only a broad criterion of stability since rocks from group (2) may give a demagnetization curve indistinguishable from those of group (1), and dispersion of a set of specimens from the same site is a more satisfactory criterion.

<u>4.5 Thermal demagnetization of NRM</u>. (Irving, Robertson, Stott, Tarling and Ward 1961) Side by side with demagnetization in alternating magnetic fields 4 different specimens from the same 11 sites were heated to successively higher temperatures. The maximum temperature in each run was maintained for only about 5 minutes to reduce chemical alteration to a minimum (Verhoogen 1962). Figure 4.4 shows a stereographic plot of the mean direction from 4 specimens at the temperatures shown for a stable (V1), partially stable (S1), and unstable (B6) site.

TABLE 4.4

Estimation of Curie Points of NRM

Site	From Precision Curve, ^{o}C.	From Intensity Curve, ^{o}C.
Plutonic Rocks		
B3	Indeterminate	Indeterminate
A2	560	540 - 560
01	550	560 - 590
G1	550	550 - 575
P1	540	530 - 580
S1	520	530 - 570
Dykes		
L1	320	275 - 380
D1	330	250 - 340
Contact Rocks		
C1	555	525 - 555
M1	about 345	300 - 400
V1	545	550 - 590

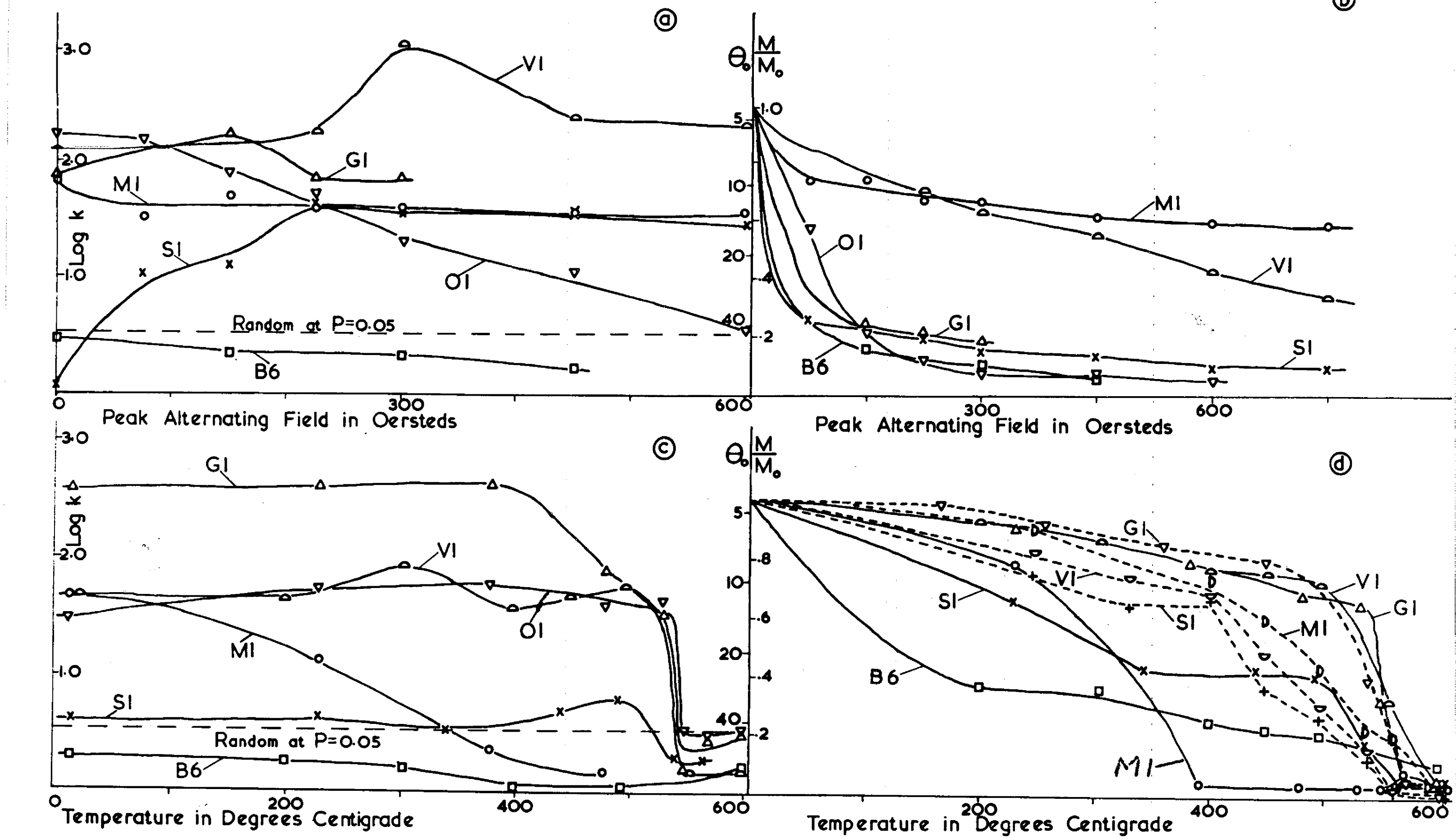


Fig. 4.6 Selected demagnetization curves from Mount Dromedary. $_o$ is the standard deviation and refers to the precision of diagrams (a) and (c). In diagram (d) full lines represent demagnetization of NRM, and dashed lines represent demagnetization of TRM given to specimens in the laboratory.

Precision plotted against temperature (analogous to the alternating field curves) (Figure 4.6c) increased after heating at most sites and reached a maximum at a temperature about 100°C below the Curie Point for the magnetic mineral in the rock. The precision, however, changed slowly with temperature until a rapid fall at the Curie Point, and at most sites there was a range of about 200°C in which the precision was not significantly different from the maximum.

The intensity of magnetization decreases very slowly with increase of temperature (Figure 4.6d) especially with stable specimens, in the lower temperature range, and very rapidly near a point that is interpreted as the Curie Point.

The Curie Point of the dominant magnetic mineral in a rock may be estimated from thermal demagnetization curves in two different ways: (1) by selecting a point on the precision curve (Figure 4.6c) at which a random level is reached: (2) by taking as the lower limit the value of T for which the gradient is greatest (Figure 4.6d), and as the upper limit the temperature at which the tangent at this point cuts the abscissa. Table 4.4 shows that these two methods are in general agreement.

If other magnetic minerals are present in sufficient quantity it is possible to estimate Curie Points from inflexions in the intensity curve. Only at site E, discussed in section 4.8, was a lower Curie Point evident. Most of the plutonic rocks,

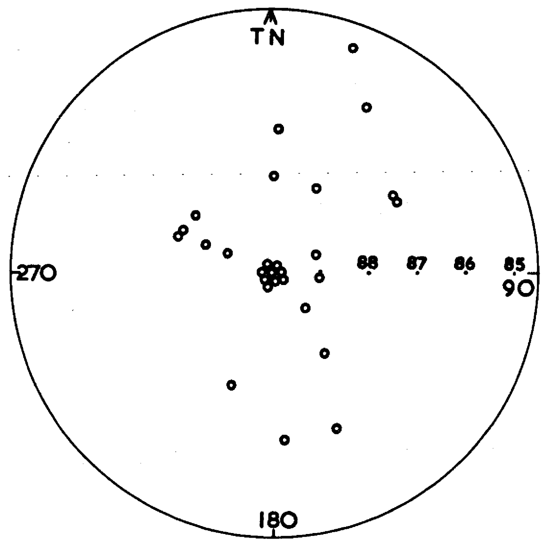


Fig. 4.7 Laboratory TRM directions from Mount Dromedary rocks. The directions are from specimens heated to 600°C, and cooled in a field vertically upwards along the axis of the specimens. Conventions as for Fig. 4.3. Only the Central portion of the diagram, in which all the directions fall, is shown.

(sites A2, 01, G1, S1 and P1) had single Curie Points between 540 and 560°C, whereas Curie Points for the contact and dyke rocks (sites L1, D1,) were between 300°C and 350°C and those for the contact rocks (C1, M1 and V1) were between 300 and 565°C.

<u>4.6 Thermal Demagnetization of TRM</u>. (Vincent, Wright, Chevallier and Mathieu, 1957). One or more specimens from each site, 28 in all, were heated above 600°C and cooled in a field of 1.1 oersted along the axis of the specimens and vertically upwards. The acquired magnetization directions are plotted in Figure 4.7. No directions deviate by more than 5° from the field direction. The mean direction is vertical ($\underline{I}$ = -90) with a precision $\underline{k}$ = 1570 ($\underline{N}$ = 28) and $\underline{a}_{95}$ = 2°. Representative normalized demagnetization curves of intensity for applied TRM and NRM are shown in Figure 4.6d. Comparison of TRM and NRM curves shows that:

(1) NRM curves tend to fall off more rapidly at low temperatures than do the TRM curves at sites A2, S1 and P2, but at higher temperatures they are nearly parallel.

(2) The TRM and NRM curves at sites 01, 02 and G1 are very similar.

(3) TRM and NRM curves are significantly different at sites V1 and M1. The TRM curves for these sites show a smooth decrease of intensity from 350 to 550°C, whereas the NRM curve for site M1 shows a Curie Point at about 350°C, and that for site V1 at about 550°C.

The comparison suggests that specimens from group (1) may contain low stability components that are removed by heating to 200°C or a chemical change may have occurred during heating in the range below 200°C. Specimens from group (2) have a Curie Point over 500°C and are not appreciably altered by heating. It seems probable that the magnetic mineral in group (3) undergoes chemical change during heating.

The smooth TRM curve at site V1 in the 200-500°C range could be explained by mixing of exsolved magnetite in ilmenite forming a range of titanium-rich magnetite minerals frozen in by rapid laboratory cooling. Site M1 requires a different explanation. The garnet-horfels at this site is very inhomogeneous, so that it was possible to measure groups of garnet-rich and garnet-poor specimens. The intensity of the former was greater by a factor of 10 suggesting that the magnetic mineral is associated with the garnet.

4.7 A comparison of the Magnetic and Thermal Methods of Cleaning.

It was shown in section 4.4 that the precision from 4 specimens after partial demagnetization in alternating magnetic fields at a variety of sites increased to a maximum that remained nearly constant for most sites over a range of fields from 100 to 300 oersteds. Similarly in section 4.5 it was shown that the thermal demagnetization gave maximum precision over a temperature ranging from 100 to 200°C below the Curie Point. Four specimens from the remaining sites were partially demagnetized in an alternating field of 150 oersteds and a separate set of 4 specimens from these sites were heated to 260°C, and those from plutonic rocks reheated to 450°C.

In Table 4.1 results are given from all groups of 4 specimens before treatment, and after treatment both in the alternating field and the temperature that yielded the highest precision. It is evident from this Table that at sites such as E3, G1, C1 and O1, the small initial scatter is due to collecting and measuring errors, and there is no significant difference in direction between groups of specimens from the same site, either before or after partial demagnetization by either method. At most other sites the precision was increased both by alternating field and thermal partial demagnetization; at sites S1, S2 and C2 the former caused the greater improvement, and the latter at site O2. Both methods of partial demagnetization increased the scatter at sites B3 and E2, whereas partial demagnetization in alternating fields increased the scatter at sites B5, L1 and D1, and partial thermal demagnetization increased scatter at sites A2 and M1.

The sites have been divided into 3 geological groups: (1) Plutonic rocks from Mount Dromedary; (2) Plutonic rocks from Little Dromedary; (3) Contact and dyke rocks. Results for these groups are shown in Table 4.5. They show that there is no significant difference between these groups, but that partial demagnetization in an alternating magnetic field gives more

TABLE 4.5

Group	Number in Group	PARTIAL ALTERNATING FIELD DEMAGNETIZATION								
		Initial				Treated				
		D	I	R	a	D	I	R	a	Q
1	10	3	-76	9.38	13	31	-80	9.75	8	2.4
2	7	55	-76	6.42	20	15	-78	6.93	7	8.3
3	4	333	-78	3.95	12	349	-79	3.90	17	0.5
Average of Groups	4^x	23	-78	3.96	10	24	-78	3.98	7	2.0
Average of Sites	22^x	17	-78	20.60	8	19	-79	21.53	5	3.0

Group1 is from Mount Dromedary, Group2 is from Little Dromedary and Group3 is comprised of dyke and contact rocks. D, I, R and a mean the same as in Table 1. Q is the ratio of the precision after partial demagnetiza-

COMPARISON OF GROUPS AT MOUNT DROMEDARY

PARTIAL THERMAL DEMAGNETIZATION								
Initial				Treated				
D	I	R	a	D	I	R	a	Q
8	-79	8.93	18	355	-83	9.10	16	1.2
179	-88	5.88	29	59	-84	6.67	15	3.4
339	-76	3.91	16	355	-76	3.93	15	1.2
15	-81	3.95	12	24	-80	3.97	9	1.5
3	-83	19.56	11	13	-82	20.61	8	1.8

tion, to that before. [x]Site VI, not included in groups 1-3, as it is probably a lava flow, is included in the over-all mean statistic.

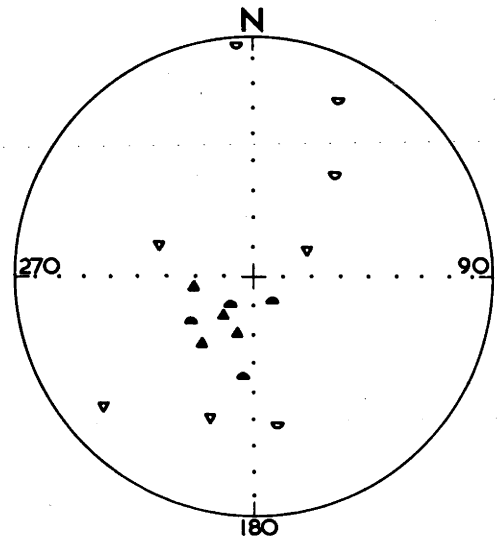


Fig. 4.8 Directions from site E1, Mount Dromedary. ∇ shows directions from specimens partially demagnetized in a peak alternating field of 300 oersteds, and ▲ shows the initial directions from the same specimens. ᗜ shows the directions of specimens heated to 540°C and ◓ shows the initial directions from the same specimens.

consistent results than thermal partial demagnetization for the plutonic intrusions, whereas for the dyke and contact rocks the reverse is true.

The good agreement of directions between groups suggests either that in each group secular variation has been averaged out or that it was smaller in the Upper Cretaceous than it is today.

It is clear from Table 4.5 that the overall mean direction is more precisely defined after magnetic cleaning than after thermal cleaning. A possible physical explanation is that the unstable components reside in areas of low coercivity (cf. Verhoogen 1959), rather than in minerals with low Curie Points, in the plutonic rocks from which the majority of these specimens were taken.

4.8 Site E1, Monzonite, a possible Example of a Self-Reversal. (Nagata, Uyeda and Akimoto 1952; Nagata 1953). The magnetization directions of specimens from site E1, which is an even-grained monzonite, initially gave a tight group in the opposite sense to those from other sites (Figure 4.8). Four specimens heated to 230°C maintained high precision in this direction, but became widely scattered after heating to 340°C, and random at 440°C. The intensity of NRM decreased rapidly to 340°C, and then slowly to 565°, whereas the intensity of specimens given a TRM fell off less rapidly with temperature. The trend of directions at 540°C was opposed to the initial direction although the scatter of points was high.

Demagnetization in alternating magnetic fields of 4 specimens initially forming a tight reversed group gave a similar, but more clearcut result. Their directions became random in 225 oersteds, and were widely scattered with negative inclinations after treatment in 300 oersteds (Figure 4.8), and in 450 oersteds the scatter increased. The intensity fell to about 3 per cent of the initial intensity after partial demagnetization in 225 oersteds, and in higher fields decreased slowly.

It would appear that after heating above 340°C and partial demagnetization in an alternating magnetic field of 225 oersteds the directions are opposed to the NRM direction, but the scatter is very high.

Examination of two polished sections revealed that the main magnetic mineral was pyrrhotite with a grain size of 0.5mm, and magnetite about a tenth of this size was associated with it.

A possible explanation of the magnetic behaviour of this rock is that the reverse NRM is due to the magnetic interaction of pyrrhotite and magnetite, and that the pyrrhotite became magnetized in the opposite direction to the ambient field as it cooled in the field of the associated magnetite (Everitt 1962). Other possibilities are the development of intergrowths such as those examined by Uyeda (1956), or self-reversal due to ionic ordering within a mineral as suggested by Verhoogen (1956). Alternatively the earth's magnetic field might have reversed between the time at which the rock at site E1 cooled below the Curie Point of magnetite, and that of pyrrhotite. In view of the absence of a reverse direction at any other Mount Dromedary site this is considered unlikely. Six specimens cooled in the laboratory from 600°C in the earth's magnetic field acquired a TRM in the same direction as the field. This is not consistent with the suggested explanation of self-reversal unless either heating has changed the magnetic minerals or the laboratory rate of cooling was too fast to allow the growth of reverse magnetization. The present results are inconclusive and a more detailed study is necessary to demonstrate a self-reversal.

4.9 Some Bulk Magnetic Properties (cf. Akimoto, 1955). The behaviour of specimens in high magnetic fields bears no direct relationship to the effect of magnetic fields of less than 1.0 oersted such as that of the earth but certain properties of specimens in high fields give some information relevent to stability problems.

Specimens selected for testing in high fields were placed in a uniform field that could be increased in steps from 300 to over 5000 oersteds. The intensity of magnetization was measured after each step. Saturated specimens, that is ones in which the intensity remained constant after the field was increased, were placed in a small uniform field in the opposite sense, which was increased in steps until the magnetization changed sign. The field required to saturate ($H_{sat.}$), the maximum isothermal remanence ($M_{i\ sat.}$), and the field required to destroy this magnetization (H_d) were obtained from the curve of magnetization intensity (M_n) plotted against applied field strength (H). $H_{sat.}$ gives some indication of the shape and size of the magnetic minerals, in general smaller magnetic grains require higher fields for saturation. $M_{i\ sat.}$ gives an estimate of the amount of magnetic material available. H_d gives the average coercivity over the whole spectrum of magnetic minerals in the rock (Cox and Doell 1960).

Table 4.6 shows values for these properties and also the intensity of NRM (M_o) the susceptibility (χ) in a field of 0.5 oersted and the ratio M_o/χ. It may be seen that values of H_d, $H_{sat.}$, and $M_{i\ sat.}$ may vary by a factor of 2 from specimens from the same site in which M_o, both in direction and intensity, is almost identical. This suggests that magnetic inhomogeneities within a site may have a negligible effect on the NRM. The ratio M_o/χ has values ranging from 0.1 to 18.0 and although many sites considered stable have values close to 1, so also do sites B4 and E1 that do not appear to be stable, whereas stable sites M1 and V1 have quite low values.

TABLE 4.6

MAGNETIC PROPERTIES

Site	Specimen	M_i sat. $\times 10^{-3}$ e.m.u./cc	H_d in Oersteds	$H_{sat.}$ in Oersteds	$M_o \times 10^{-3}$ e.m.u./cc	$\chi \times 10^{-3}$ e.m.u./cc	M_o/χ
B1	23A1				.19	4.2	.046
B2	25A1				.50	3.3	.15
B3	40A1	16	220	1600	.47	6.0	.079
	40A3				.26	3.4	.075
	41A	29	400	1500	.42	1.3	.33
B4	55A				1.6	.81	1.9
A1	20.1				1.9	3.0	.64
A2	37A1	20	500	1200	.39		
E1	7A	45	380	1100	2.6	3.0	.87
E3	16A				2.2	6.3	.34
01	11B	1400	560	3000			
	12A				2.8	2.7	1.0
	13A	600	250	2500	3.0	4.0	.75
02	14A1	600	1000	1100	2.1	2.8	.75
	14A2				4.1	3.5	1.2
03	6A2				5.9	4.7	1.3
	5B	1400	580	1800	4.7	-	-

G1	33A	700	1000	250	3.9	4.4	.87
P1	45B				7.8	18	.23
P2	48A	480	450	1150	2.1	-	.11
	48B	-	-	-	1.8	10	.10
	49A	300	180	700	2.1	-	-
S1	42B	120	425	1150	.68	5.4	.13
	44B	110	1250	275	.86	4.2	.20
L1	31A1	160	4500	850	2.7	.17	16.0
	31A2				2.6	.13	19.0
D1	27A1				.046	.033	1.4
	27C1	0.9	220	500	.027	.12	.22
	28A2	2.6	400	2000	.027	.080	.34
C1	19A2				4.4	3.2	1.4
C2	29A				.67	.14	4.7
	29B	155	550	1500	.89	-	-
M1	52A2				.047	.15	.32
	53A1	> 0.6	900	> 7000	.055	.16	.35
V1	9A				3.6	9.9	.36

It is seen that although the bulk magnetic properties have some bearing on the stability of the NRM of rocks it is not a direct one, and none of them provide an unequivocal criterion of stability. This is presumably due to the fact that the NRM derives from only a small part of the magnetization available in the ferrimagnetic minerals, whereas the bulk properties are due to all the magnetic material available.

4.10 Mineragraphic Investigations. Results of polished section and powder photography work are summarized in Table 4.7. The polished sections examined were not necessarily representative of the rock since the minerals in some samples, such as those from sites G1, P1, O1 and M1, were unevenly distributed. It was not always possible to identify all the opaque minerals present, particularly where they occurred in extremely small grains, as in the sections from sites M1 and C1, but they must be present since the rocks showed ferrimagnetic properties.

The following points emerged from the examination of 15 sections:-

(1) A very variable proportion of the opaque minerals are not magnetic, so that there is no simple relationship between opaques in thin section and amount of magnetic mineral present.

(2) Although minerals of the magnetite-ilmenite series predominate, pyrrhotite is commonly present, and at sites E1

and C2, the quantity is sufficient to affect the magnetic properties of the rock.

(3) At site E1 the juxtaposition of magnetite and pyrrhotite crystals suggests a possible mechanism for magnetic self-reversal in this rock.

(4) It was not possible to distinguish intermediate minerals in the magnetite-ilmenite solid solution series in polished section.

(5) Intergrowths of magnetic minerals were visible in a number of the sections, and information regarding the relationships of the magnetic minerals could give valuable clues to the magnetic behaviour of the rocks.

(6) X-ray powder photography, both of powder from selected crystals, and from the magnetic fraction of ~~a~~ rock crush provides both confirmation of and information additional to that of the polished sections.

This work confirms (Nagata and Ozima, 1956; Nagata, Uyeda and Ozima, 1957; Vincent et alia, 1957) that valuable information relating to magnetic properties and peculiarities (such as self-reversals) can be gained from polished section examination.

<u>4.11 Discussion</u>. The following points indicate that the direction obtained at Mount Dromedary is that of the earth's magnetic field in the Cenomanian Epoch:-

1. Studies of alternating field and thermal demagnetization show that, apart from secondary components at some sites which can be removed by partial demagnetization, the magnetization is stable.

2. Contact rocks heated by the intrusions are magnetized in the same direction as the igneous rock, indicating that the magnetization originated at the time of cooling.

3. At some sites demagnetization curves of TRM and NRM are the same indicating that the NRM is in fact a TRM, and does not comtain an IRM component.

4. One or more specimens from all sites cooled in the laboratory from 600°C in a known magnetic field acquired a magnetization accurately parallel to the ambient field (Figure 4.7), showing that the magnetism is isotropic.

5. Rocks from different physical and chemical environments, (dykes, margins and interiors of over- and under-saturated plutonic masses, and in which stresses, load, and chemical equilibria have been different, are magnetized in a similar direction.

6. K-A isotope age determinations on several minerals from 3 sites gave an age close to 90 m.y.

7. The range of sampling sites is adequate to average out secular variation.

Thus the pole position of 56S, 136E, calculated from the magnetically cleaned Mount Dromedary rocks, in which the polar errors are dm=9, dp=9, and which are known to be of Cenomamian age, is well defined both in time and space.

CHAPTER 5. BRISBANE TUFF.

5.1 Geology and Sampling. The Brisbane Tuff is rhyolitic, and was extruded during the deposition of the Ipswich Coal Measures which contain a rich fossil flora of Middle Triassic age (Jones and de Jersey 1947). Bryan and Jones (1960) have noted five different varieties of tuff. The welded, unstratified tuff (Richards and Bryan 1934) was, however, the only variety from which fresh samples suitable for palaeomagnetic work could be obtained, because it had been quarried for building stone in and around the city of Brisbane. The tuff forms lenses in beds that are either horizontal or dipping less than ten degrees. A thin section from each site shows a remarkable uniformity, both of texture and composition, and it is likely that the 6 sites represent a very small time interval. It is a porphyroblastic rock with a very fine groundmass. Some of the porphyroblasts of quartz and felspar are embayed and some minerals are deuterically altered. This alteration probably occurred immediately after extrusion and there is no sign of weathering.

Evidence of attitude is scant, but the boundary between two units (sites S1 and S2), each about 30 feet thick, exposed in Stafford quarry, is horizontal. A dip of forty degrees in the beds underlying the welded tuff at the north end of the Windsor quarry (site W) is exceptional, and decreases rapidly to the

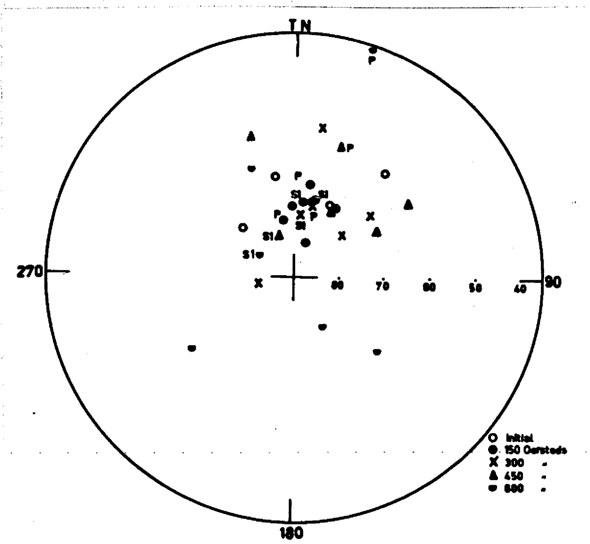


Fig. 5.1 Directions from partially demagnetized specimens of Brisbane Tuff. One specimen from each site was subjected to an alternating magnetic field of which the peak value was increased by increments of 150 up to 600 oersteds. Conventions as for Fig. 5.3

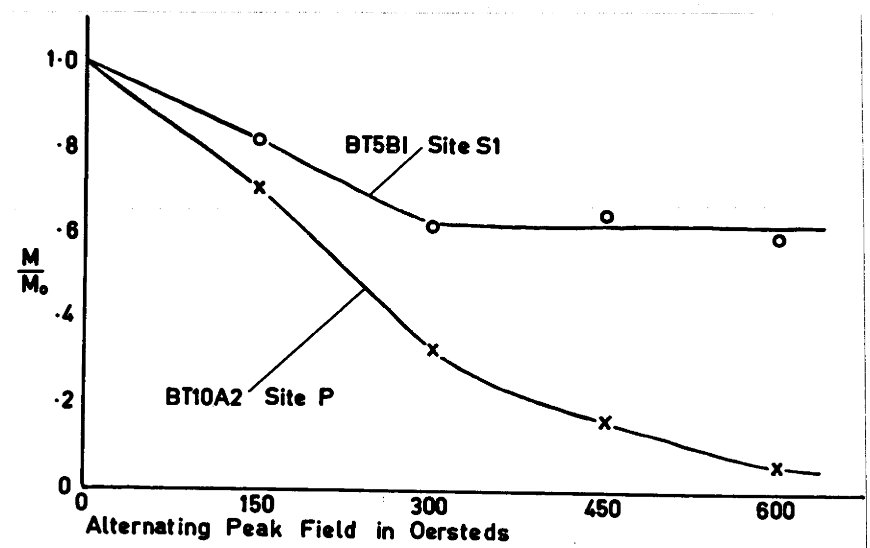


Fig. 5.2 Alternating magnetic field demagnetization of the Brisbane Tuff. The ordinate gives the ratio of the intensity of magnetization remaining after treatment ($\underline{M}$) in the peak alternating field recorded along the abscissa, to the initial intensity of magnetization ($\underline{M}_o$).

south. It seems probable that the tuff fills depressions in the Triassic land surface and has not been tilted by more than a few degrees, so that oriented specimens were related to a horizontal plane and not to the bedding. Charred remains of trees overwhelmed by the tuff suggest extrusion at high temperatures.

Two oriented specimens were taken from each of six sites, treating each flow at Stafford quarry as a separate site. Three discs, each of 35 mm diameter and 7 mm thick, were cut from each sample, giving 36 specimens.

5.2 Partial demagnetization in Alternating Magnetic Fields.

As an initial test of stability of the NRM, a single specimen from each site was subjected to alternating magnetic fields increased in 150 oersted steps up to 600 oersteds. The directions obtained are plotted in Figure 5.1. An alternating field of 150 oersteds gave the smallest scatter, and all specimens were treated in this field. The scatter remained small in fields up to 450 oersteds.

Figure 5.2 shows alternating field demagnetization curves for the most stable (site S1) and least stable (site P) specimens. Curves for other specimens lie between these two. It may be noted that the directions after treatment in high alternating fields (Figure 5.1) are least scattered in the specimen from site S1 and most scattered in the specimen from site P.

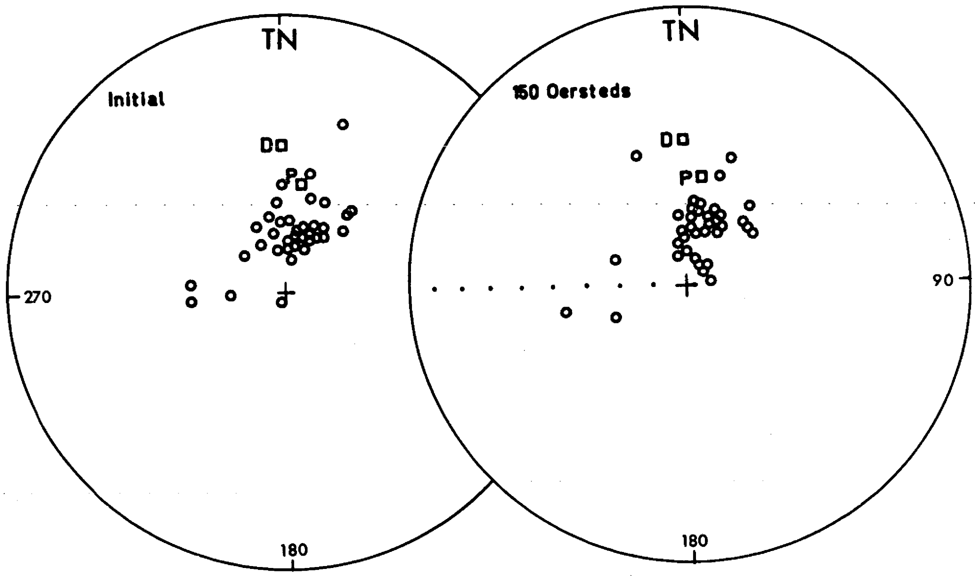


Fig. 5.3 Directions of remanent magnetization from the Brisbane Tuff. North-seeking directions are plotted as open circles on the upper hemisphere of a Schmidt equal area projection, before and after magnetic cleaning in an alternating field of peak value 150 oersteds. The dipole (D) and present (P) field directions are shown.

5.3 Results. The directions in all specimens measured initially (NRM) and after partial demagnetization in an alternating magnetic field of 150 oersteds are plotted in Figure 5.3. The mean site directions and statistics at the (1S) and (1st) level are listed in Table 5.1.

The statistics in Table 5.1 show that the precision increases after treatment only at sites W1 and P. However, the resultant direction obtained after treatment is slightly further from the present and dipole field directions, suggesting that a small viscous component is preferentially removed by this treatment.

Table 5.2 gives the estimate of within (w) and between (b) site precisions. (Watson and Irving 1957).

The increase in between-site precision after treatment (b,52→145) indicates that a small component, different for each site, is reduced or randomized by the alternating field. The improvement in K^1 and α^1 is not large because the initial directions are caused predominantly by a stable component.

All the specimens measured were normally magnetized, whereas preliminary results from the Brisbane Tuff reported in Irving and Green (1957) indicated that some specimens were reversely magnetized. These specimens were collected by Mr. I.R. McLeod of the Bureau of Mineral Resources. They were measured by Dr. Green and reported in the above paper. It is possible that

TABLE 5.1

BRISBANE TUFF SITE DIRECTIONS AND INTENSITIES

			M_n					M_{150}				
Site	S	N	D	I	R	a	M_o	D	I	R	a	$\frac{M}{M_o}$
W1	2	6	352	-69	5.96	6	7.7	9	-72	5.97	5	0.75
S1	2	6	7	-76	5.98	4	16.8	7	-78	5.97	6	0.82
S2	2	6	32	-70	5.98	4	10.1	39	-68	5.95	7	0.98
K	2	6	26	-62	5.95	7	2.2	19	-68	5.72	16	0.64
P	2	6	16	-66	5.83	13	19.9	9	-70	5.97	6	0.73
U	2	6	292	-74	5.80	14	0.6	311	-77	5.55	21	0.86
Combined 1st level	6	36	7	-72	5.89	10	-	11	-74	5.94	7	-

M_n gives the NRM results, and M_{150} those after partial demagnetization in an alternating magnetic field of 150 oersteds. S is the number of samples and N the number of specimens. R is the length of the resultant giving each specimen unit weight, and D and I specify its direction. a is the half-angle of the cone of confidence at P = 0.05. The combined values have been obtained by applying Fisher's statistics to the mean site directions giving each unit weight. M_o is the average intensity of magnetization in e.m.u./cc x 10^{-6}. $\frac{M}{M_o}$ is the ratio of intensities after and before partial demagnetization.

these reversed directions were from a lower horizon than those described here, however the within site scatter of directions was very high in the reversed sites, which may have been due to instability.

TABLE 5.2

WITHIN AND BETWEEN-SITE ANALYSIS OF PRECISION

	Initial	Treated	
w	61	35	Watson and Irving
b	52	145	
k^1	271	512	
α^1	8.6	6.2	
$\alpha^{1\gamma}$	4.4	4.6	Fisher
α^{1sT}			

k^1 = estimate of precision after allowing for palaeomagnetic errors, which appear in the within-site precision.

α^1 = the half-angle of the 95% cone of confidence after Watson and Irving 2-tier analysis.

At all sites the specimens were oriented relative to a horizontal plane. Bedding in sediments beneath is usually flat but variable dips occur at Windsor quarry. The specimens from different sites are tightly grouped (see Figure 5.3). This could only be the case if after magnetization the tuff underwent no relative movement between sites, implying that the tuff at site W1 cooled in its present attitude and has not been folded conformably with the underlying strata. This confirms the likelihood that the tuff fills depressions in a previous land surface.

The pole position calculated from the (1st) statistics is (57S, 143E) with polar errors dm = 13, and dp = 12.

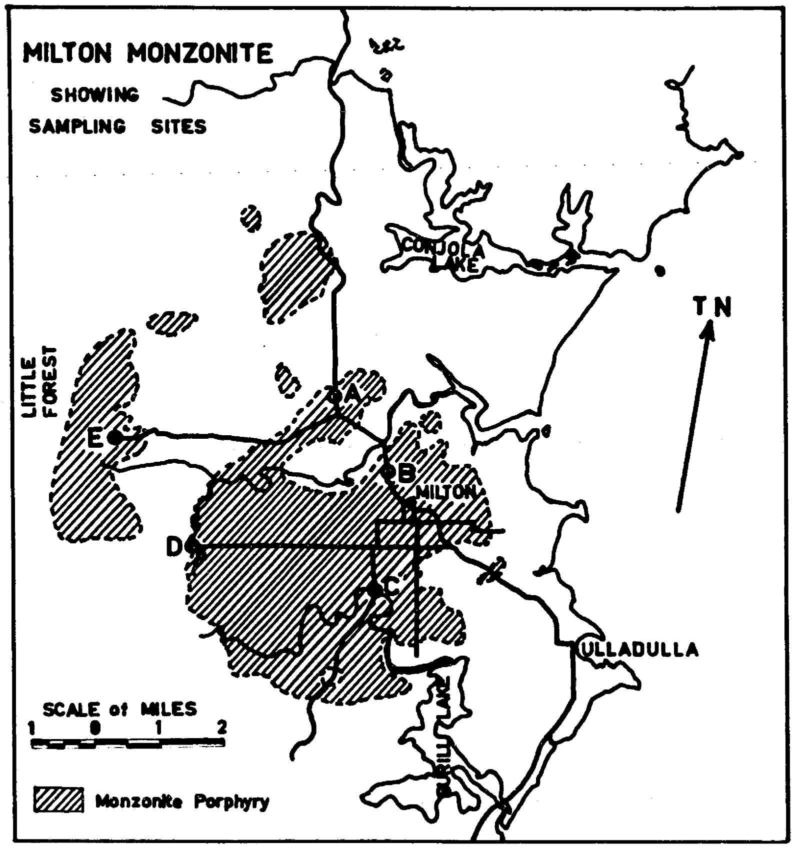


Fig. 6.1 Sketch map of Milton Monzonite, showing sampling sites.

CHAPTER 6. MILTON MONZONITE.

6.1 Geology, Age, and Sampling.

The monzonite porphyry of the Milton district intrudes shattered and tilted Lower Palaeozoic sediments, and sub-horizontal sediments of the Upper Marine Series of Permian age. The intrusion is in the form of an irregular laccolith with associated sills (Brown 1925). The fact that the enclosing Permian sediments have not been tilted suggests that there has been no movement since emplacement.

The monzonite is invariably porphyritic, and albitization is common, and much of the outcrop is weathered and soil covered. However unweathered oriented samples were collected from 5 sites, a quarry, a road-cutting, and two sites from river beds spaced over the main mass on which the town of Milton stands (Figure 6.1), and a road-cutting from the sill-like intrusion of Little Forest.

Preliminary K-A isotope age determinations have been made on plagioclase and pyroxene separates, giving a minimum age of 160 m.y. (Richards, private communication). These indicate a pre-Middle Jurassic age. Thus the porphyry was intruded at a time between Middle Permian and Middle Jurassic on the Kulp time scale.

6.2 Partial Demagnetization in Alternating Magnetic Fields.

Directions of NRM at sites A and C showed a wide scatter suggesting the presence of a large secondary component. Four specimens from each of sites A, B and C were remeasured after treatment in alternating magnetic fields, increased by steps. The mean site

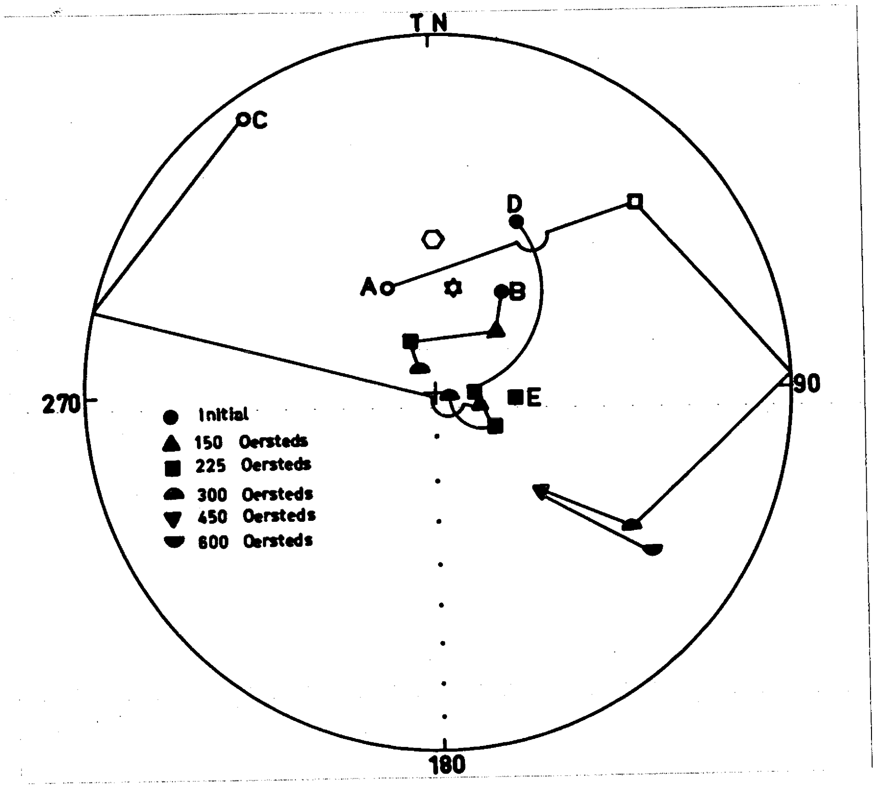


Fig. 6.2 Mean site directions after successive partial alternating field demagnetization. Conventions as for Fig. 5.3.

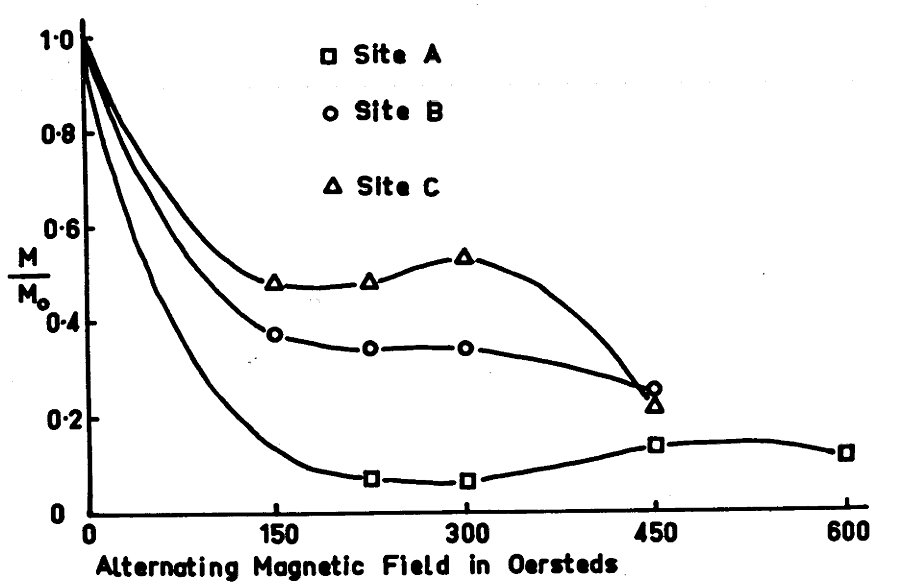


Fig. 6.3 Alternating field demagnetization curves for sites A, B, and C. Comparable with Figs. 5.2 and 4.6(b).

direction after each treatment is given in Figure 6.2. In all cases partial demagnetization in an alternating magnetic field moved the site directions away from the present field, but the scatter remained very great at site A. All specimens were treated in 225 oersteds, and the site means, apart from site A, form a coherent group.

Demagnetization curves for sites A, B and C are given in Figure 6.3. The rapid initial fall of intensity is due to the removal of a large 'soft' secondary component, and the initial direction at site C indicates that much of it is directed along the present field direction. Hence the increase in intensity at site C after treatment in 300 oersteds, and at site A after 450 oersteds, is due to an increase in the resultant of two opposed vectors due to the more rapid removal of the one directed along the present field. Nevertheless the primary vector at site A is diminished to such an extent by the demagnetizing field that the directions remain random at P=0.05 and have not been used in the analysis.

Partial demagnetization at sites B and C gave the highest precision after treatment in 300 oersteds and it is possible that a higher precision could be obtained by treating all specimens in this field, but the mean directions would not be significantly changed as may be seen by site directions in Figure 6.2. It appears that the secondary component acquired by

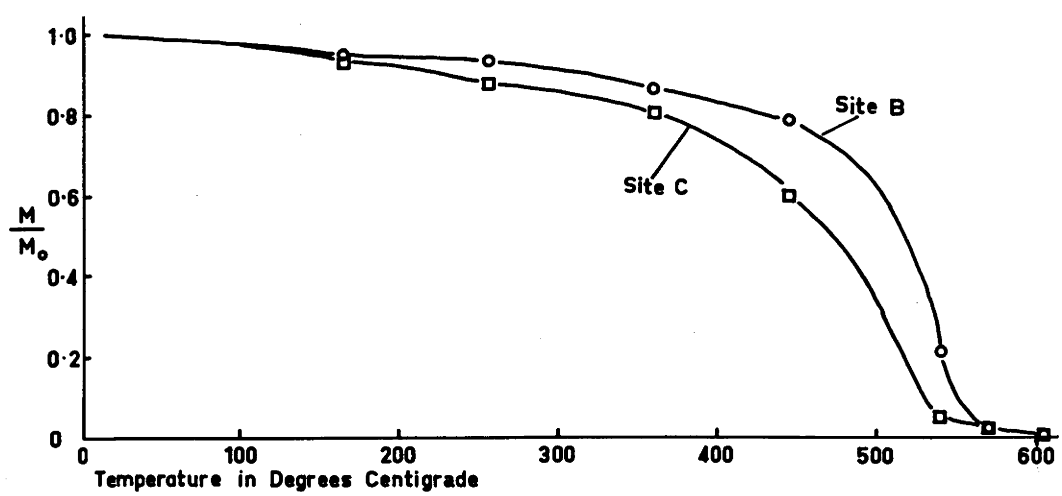


Fig. 6·4 <u>Demagnetization of laboratory TRM for sites B and C.</u> Comparable with Fig. 4·6(d) dashed lines.

this rock has a higher coercivity than that of lavas treated elsewhere, such as the basalts of New South Wales (Irving, Stott and Ward, 1961) and those of south-east Queensland (Chapter 10), since maximum precision occurs here after treatment in a higher alternating field.

6.3 Demagnetization of Applied TRM by Heating. Four specimens from each of sites B and C were heated to 600°C and cooled in an applied field of 1.1 oersteds. The TRM directions acquired were within 1° of this field except for one specimen, which deviated from it by 4°. This shows that the specimens are magnetically isotropic and suggests that they acquire a TRM which accurately parallels the field in which they cool when it is comparable in magnitude with that of the earth.

The ratio of TRM to NRM for the specimens at sites B and C is respectively 16 and 20. If we assume that the magnetic field in which the monzonite originally cooled had the same intensity as that applied in the laboratory (1.1 oersteds), this indicates that over 90 per cent of the original TRM has decayed since the time of formation, and suggests that the NRM in similar but much older rocks may be too weak to measure.

The specimens were demagnetized by heating to successively higher temperatures and the normalized intensities are plotted in Figure 6.4. For site C the intensity falls off slowly with

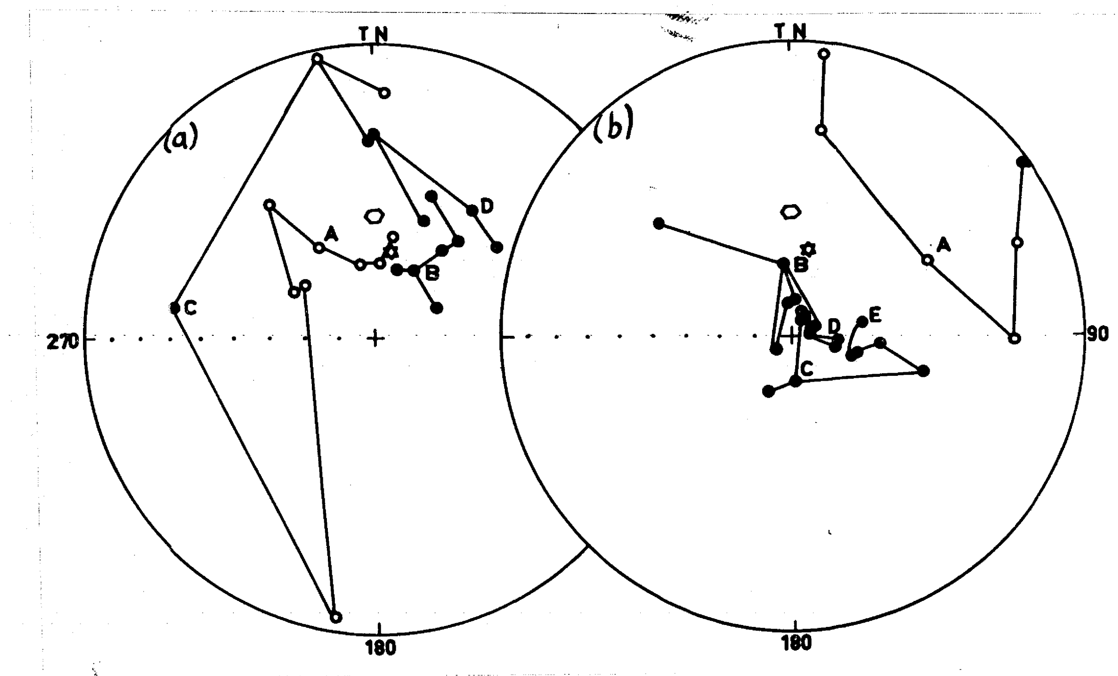


Fig. 6.5 Directions of magnetization from specimens before (a) and after (b) partial demagnetization in an alternating magnetic field of peak value 225 oersteds. Conventions as for Fig. 5.3.

increase of temperature up to 400°C, for site B even more so. The curves indicate that the main Curie Points lie between 500°C and 540°C for site C, and between 530°C and 570°C for site B. In this instance the site with the higher Curie Point is the more stable but the difference is too small and the temperature spacings too wide for this to be significant.

6.4 Stability and Results. The following points indicate that the directions after partial demagnetization in alternating fields give that of the field at the time of cooling:-

(1) Specimens acquire TRM directions in the laboratory accurately along the applied field.

(2) The directions are well away from the present field direction so that they are stable in this field.

(3) Alternating field demagnetization curves are typical of those from partially stable rocks.

(4) TRM curves indicate stability under all temperature conditions likely to have prevailed since intrusion.

Table 6.1 gives the mean site directions before and after treatment in an alternating field of 225 oersteds and the combined statistics at the 1sΥ and 1Υ level, and the individual specimen directions are plotted in Figure 6.5. The result gives a field direction in the opposite sense to the present field and with a steeper inclination, and the pole position calculated

TABLE 6.1

MEAN SITE DIRECTIONS FOR THE MILTON MONZONITE

			M_n					After Magnetic Cleaning in 225 Oersteds					
Site	S	N	D	I	R	k	α		D	I	R	k	α
A	3	6	336	-63	5.7	25	14		48	-23	5.06	5.3	32
B	3	6	34	+62	5.89	46	10		333	+77	5.69	16	17
C	3	6	326	- 6	2.66	1.5	-		119	+75	5.75	20	15
D	2	4	27	+46	3.83	18	23		88	+81	3.98	125	8
E	1	2	-	-	-	-	-		94	+72	1.99	-	-
Combined at 1sr level	3	16	1	+39	2.360	3.1	55	Sites 4	85	+81	3.923	39.0	15
Combined at 1r level	-	16	11	+48	10.35	2.6	28	N ~~#~~18	79	+83	17.034	17.6	9

from the treated 1st statistics gives a pole at (32S, 171E) with polar errors dm=29, dp=29.

CHAPTER 7. GIBRALTAR SYENITE, PROSPECT DOLERITE AND GINGENBULLEN DOLERITE

7.1 Introduction. When I came to the Department Boesen and Irving had carried out initial palaeomagnetic work on the Gibraltar Syenite, the Prospect Dolerite, and the Gingenbullen Dolerite. Subsequently I carried out stability tests on the specimens from these intrusions and collaborated in a joint publication (Boesen, Irving and Robertson 1961). The work is described here to preserve the chronological order of the rock bodies studied.

7.2 Geology, Sampling and Age. The Gibraltar Syenite is thought to be an asymmetric laccolith and is intruded into Hawkesbury Sandstone (Stevens 1956), which is Middle Triassic. It is composed of an aegenine-augite microsyenite with deuterically altered phases and narrow pegmatitic veins. The samples were obtained from 2 operating quarries on the southern face, for which grid references on the one mile military series are Mittagong 426426 and 427424. On petrological grounds the intrusion was regarded as probably early Tertiary (David 1950 p.581), but hornblende from this work gave a K-A isotope age of 178 m.y., placing it in the Lower Jurassic on the Kulp time scale. Thus geological and K-A isotope evidence put the age limits at Middle Triassic to Lower Jurassic.

The Prospect Dolerite is a dish-shaped sheet of teschenitic dolerite convex downwards, intruded discordantly (at least in